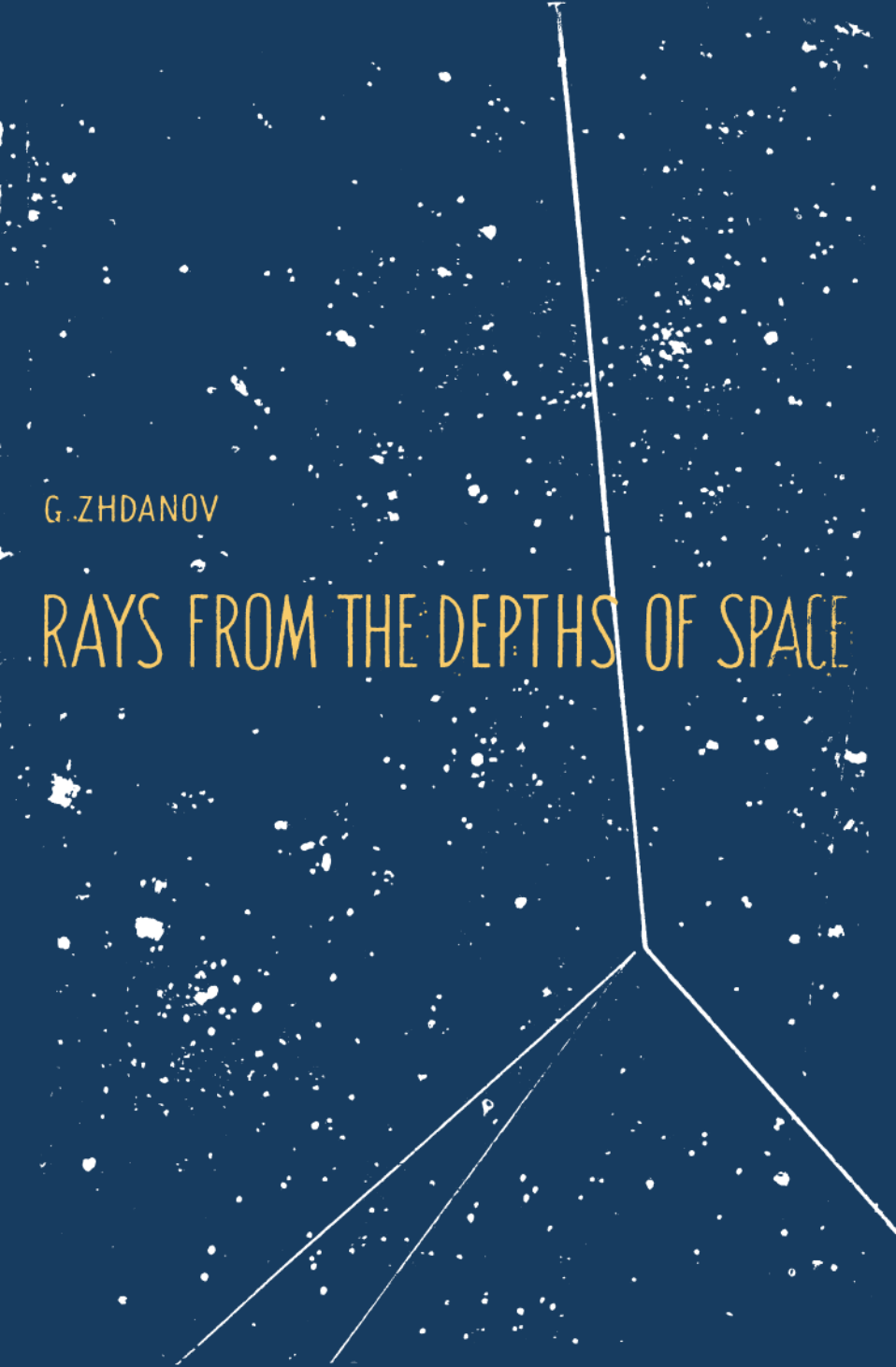
G. ZHDANOV

RAYS FROM THE DEPTHS OF SPACE



G. ZHDANOV

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INTRODUCTION

Looking back over the path traversed by science during the first half of this century, one is struck by the enormous progress made in the study of the structure of matter. A whole series of extremely interesting discoveries enabled research workers to probe the depths of the atom and open up many peculiarities of the microcosmos.

In this long but logically consecutive series of attainments of human thought, the development of science proceeded hand in hand with technological progress, receiving from the latter delicate and intricate measuring tools and creating better and more powerful means to transform the world about us. A decisive step in this direction was made when scientists found ways of attacking atomic nuclei, ways of altering their composition and properties.

But scientists were still poorly informed about the peculiarities and the essence of processes going on within atomic nuclei. A new and exceptionally powerful means of probing the secrets of the constitution of matter came with the study of cosmic rays, those invisible rays of enormous penetrating power, which were discovered some forty years ago but which have been investigated in more or less detail only recently. During the past two decades the science of cosmic rays has grown from a second-rate branch of physics, related, it would seem, only to certain specific phenomena in the atmosphere, into one of the leading divisions of modern physics. One needs only mention that cosmic ray studies led to the discovery of several previously un-

known elementary particles (the positron and mesons) and of entirely new properties of the known particles of matter, and also new phenomena and processes involving the tremendous energy of particles of cosmic radiation.

More, it was precisely cosmic rays that enabled scientists to learn of forms of matter which in the full sense of the word stand on the border-line between matter and radiation and possess many of the characteristic physical properties of both. This once again and more convincingly pointed to the material nature of radiation; thus Lenin's theory of matter was confirmed by new and important findings. The processes observed in cosmic rays are the most brilliant illustration of the fact that matter is constantly passing from one form into another; in such processes, particles of matter are continuously being converted into radiation and back again. And contrary to former thinking, the contrasting of matter and radiation is in itself no longer of crucial importance.

Cosmic rays are of interest primarily from the viewpoint of studying the atomic nucleus and the elementary particles of matter.

All this does not mean that in the field of cosmic radiation we are no longer confronted by problems and beset with puzzles. We need only recall that the very origin of these rays is far from a definitive solution.

It is hardly possible at present to speak of any technical application of cosmic rays, but there can be no doubt that the already known and in part accomplished methods of creating "artificial" cosmic rays will give man a new and exceedingly peculiar instrument for acquiring knowledge and possibly for transforming nature. This will doubtlessly serve as one more illustration of the well-known principle of dialectical materialism which states that man provides complete proof of his ability to learn and understand the phenomena about him by re-creating these phenomena in the proper conditions and by making them serve his aims.

This book sets out to relate how the principal phenomena of cosmic radiation were discovered and how these problems are now being tackled by scientists. An attempt has been made to introduce the reader to the present-day concepts and problems dealing with the properties not only of cosmic rays but also of particles of matter in general. Despite the extreme complexity of the subject, it is undoubtedly of considerable current interest.

It was also the writer's intention to show the role of Soviet physicists in cosmic ray studies. The works of such Soviet scientists as S. Vernov, D. Skobeltsyn, Y. Terletsky and others open up new avenues to the solution of cardinal problems in the field of cosmic rays.

In writing this book, the author had in mind the average reader. All mathematical calculations have been avoided and only the basic physical concepts are given in the text.

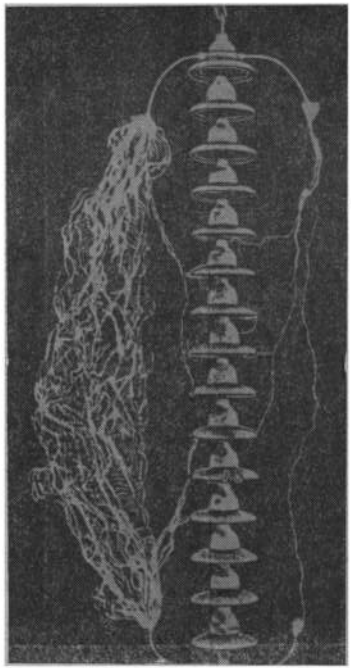
Chapter I

BAD LUCK
THAT OPENED THE WAY TO A DISCOVERY

For many years physicists and engineers were beset by the question of whether air conducts electric current or not. An investigation of this problem led to one of the most remarkable discoveries of the twentieth century.

As far back as the eighteenth century it was firmly established that objects not connected with the earth retain for a long time the electric charge imparted to them; at any rate, the loss of the charge through insulation is, as a rule, greater than through the surrounding air.

Gradually facts were accumulated that cast doubt on the seemingly unquestionable insulating properties of air. For how does an electric arc burn in the air, how does a spark jump, or how do tongues of lightning leap (Fig. 1)? Why are high-tension electric wires (with voltages of the order of many thousands of volts) surrounded by corona? All these phenomena are nothing but different types of electric discharge in the air. In short, they are proof that electricity can flow in the air and cause various light and sound effects. Apparently, the electric properties of air, which ordinarily is a good insulator, can under certain conditions be altered, as witness the well-known fact that thunderstorms with lightning occur only in air saturated with moisture. In laboratory experiments it was noted that a reduction in the air pressure in the gap between two electrodes,



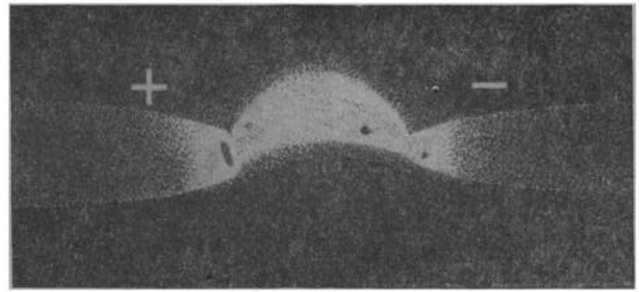


Fig 1. A spark, an electric arc, and lightning. These are phenomena in which electricity flows through the air

to which a definite voltage (several hundred volts) was applied, increases the electric conductivity of this gap. If the vacuum between the electrodes is sufficient, a discharge takes place even if the distance between them is several tens of centimetres.

It was soon found that even in the ordinary state, air (or any other gas for that matter) can, though very feebly, pass electric charges. This is proved by the following fact. The leaves of an electroscope which have been insulated from the body of the instrument and the earth as carefully as possible (Fig. 2), gradually lose their charge in the course of several days and fall. Special, accurate experiments have established the fact that practically all the loss of charge is through the air and not via the insulating material.

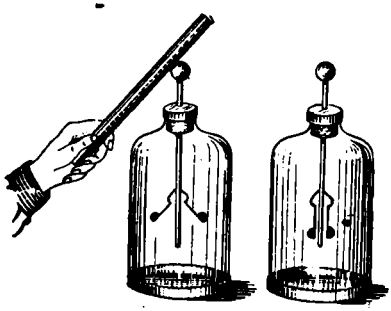


Fig. 2. A simple electroscope

At one time it appeared that the electric conductivity of air was due to the presence of already known invisible rays. It was found, for example, that X-rays, first discovered in 1895, enable the air to conduct electricity rather well. Irradiation of a charged electroscope with these rays makes the leaves fall quickly. In 1896, the French physicist Becquerel established the existence of new, still more penetrating rays emitted by uranium. Under the action of these rays, the air also becomes a conductor of electricity. It was soon discovered that a large number of chemical elements emit the same rays as uranium. From one of them, radium, came the name "radioactive elements," and the phenomenon became known as radioactivity.

Further experiments brought out the complex composition of radioactive radiation. Radioactive substances emit elec-

trically charged particles: the so-called alpha particles that have a positive charge and the beta particles with a negative charge; in addition, they emit invisible rays which have properties very similar to those of X-rays. These were called gamma rays. They are readily distinguishable from alpha and beta particles because they easily penetrate (even better than X-rays) such dense substances as lead, whereas the alpha and beta particles are absorbed by even a millimetre-thick layer of aluminium.

It must be noted that science still retains for alpha and beta particles also the term alpha and beta *rays*. Certain properties (the way they affect a photographic plate and their ability to ionize air) at first caused a stream of alpha and beta particles to be regarded as a sort of invisible rays. As will be seen further on, it was still more difficult in the case of cosmic radiation to differentiate between rays and a flow of fast charged particles.

How can the fact that air loses its insulating properties when acted upon by X-rays and radioactive rays be explained? The explanation given even at the time of the discoveries of Roentgen and Becquerel was simple enough.

It was established by experiment that powerful X- or gamma rays can break up the molecules of the air, and in general any gas, into electrons and positive ions. The positively charged ions and electrons resulting from such a process (known as ionization) begin to move in opposite directions in any gap between two oppositely charged bodies. That is exactly how any electric discharge caused by ionizing rays in gases begins. Therefore, the reason for the rapid discharge of the electroscope when undergoing irradiation lies in ionization of the air due to rays (Fig. 3).

It would appear that not much is required to confirm the validity of this explanation: charge an electroscope, the leaves of which are sufficiently well insulated from the body, and see that no ionizing rays get into the air. In such a case, the charge of the leaves should be retained intact practically an unlimited time. However, the task proved far

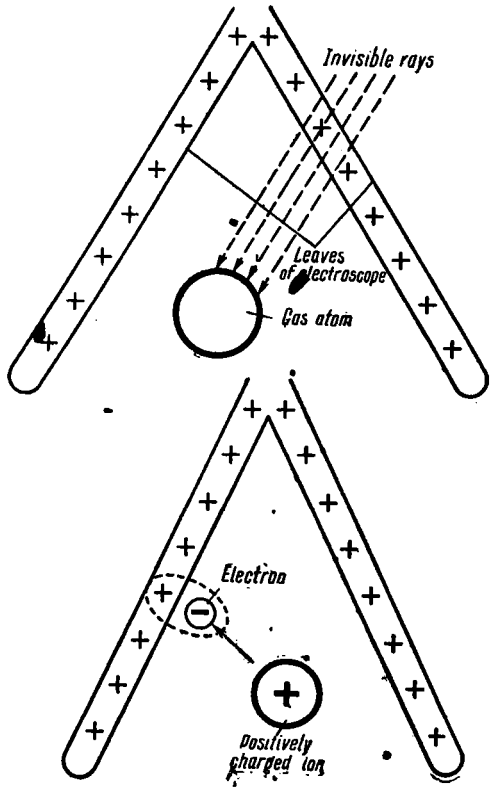


Fig. 3. Ionization of a gas atom and the discharge of an electroscope by the action of invisible rays

from simple. These very same radioactive substances, which in the earlier experiments did not in the least manifest themselves, suddenly began to be detected everywhere, in rocks, in the soil, in water and in the air itself, true, in negligible quantities. It need only be recalled that an average of one charged particle (alpha particle) emerges every few hours from each square centimetre of surface of

an ordinary metal object. This particle, whose birth is due to a minute admixture of radioactive substance, breaks up as many as one hundred thousand molecules of air into ions.

No matter where the test measurements were made, in glaciers, lakes, in the open sea, on high towers or snow-covered mountain peaks, ionization of the air was detected everywhere, though on the ground it was greater.

Finally, in 1909 the Swiss physicist Göckel decided to "get rid" of this ubiquitous radioactivity once and for all: he took his instruments in a balloon to a height of four kilometres above sea level. It would seem that the success of such an undertaking, a thing far from safe in those days, was ensured. Indeed, all the known rays capable of ionizing the air, and these included the most penetrating gamma rays, are practically absorbed *in toto* in a hundred-metre layer of air, and the heavy radioactive gases that emit these rays should likewise not extend to such extreme altitudes above the earth's surface. And what was the result? Göckel was astonished: instead of escaping the influence of ionization he found that the rate of discharge of the electroscope increased several times over!

The result obtained was so difficult to grasp and so unexpected that Göckel's report was regarded incredulously. Many scientists decided to repeat Göckel's experiment. Between 1911 and 1914, the physicists Hess and Kolhörster reached still greater altitudes. And when the balloons reached their limit, sounding balloons with complex self-registering instruments were sent up into the upper layers of the atmosphere, the stratosphere. The instrument shown in Fig. 4 was constructed by the American physicists Millikan and Bowen who in 1922 sent it up 15.5 km. It turned out that at this great altitude ionization of the air was far from being less than at sea level; on the contrary, it was more by tens of times.

How was such a puzzling thing to be explained by the conceptions that existed at the beginning of the twentieth

century? At first, many believed that some previously unknown and strongly ionizing radiation of the gamma ray type was constantly being produced in the atmosphere itself; and for some totally inexplicable reasons this radiation increased as the air became rarer with increasing altitude.

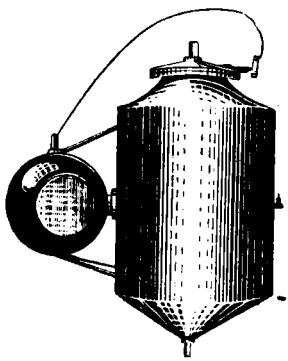


Fig. 4. The first self-recording instrument made by Millikan and Bowen. It is used to register automatically ionization of the air by rays at high altitudes

This belief was supported by Millikan's first experiments and those of others dealing with the absorption of the new rays in matter. The recording instrument was surrounded by layers of lead of various thickness. It was found that the absorption of these rays by relatively thin lead shielding (up to 5 cm.) was marked. The conclusion drawn was that such rays do not possess great penetrating power and, consequently, cannot come to the earth from outer space.

However, absorption in lead cannot be compared with absorption in air. Further on, it will become clear that the reason for this is that the atomic weight of lead is nearly 15 times that of air, and therefore chemical substances should have been used whose atomic weight is close to that of the air; such as water for example.

In the summer of 1925, Professor Mysovsky of Leningrad and his pupil Tuvim made the first reliable studies of cosmic ray absorption in water. They lowered their electroscope into the waters of Lake Onega to a depth of 10 m. It appeared that absorption of ionizing radiation in water fully corresponds to absorption in atmospheric air if the layers of water and air are *equal in mass.*

Similar results were obtained in the same year by Millikan whose experiments slightly differed from those of Mysovsky and Tuvim. Millikan compared the intensity of the ionizing rays in the waters of two mountain lakes situated at altitudes of 3.5 and 1.5 km. above sea level. It was found that the two-kilometre layer of air between these lakes could very well be replaced in terms of absorption by about two metres of water in the upper lake. Now note that a two-metre column of water and a two-kilometre column of air of the same cross-section weigh nearly the same. It will then be clear that both in the air and in the crystal clear water of mountain lakes no radioactive rays of any kind are formed, and what takes place is merely the gradual absorption of some sort of radiation incident from above.

A still more remarkable fact was discovered by Mysovsky and Tuvim in 1926. They conducted measurements for a long period, and for the first time established a definite relationship between the intensity of the radiation under study and the air pressure. It was found that in contrast to the sun's rays, these rays fall on the earth's surface almost uniformly at all times, day or night. However, a careful correlation of the readings of an electroscope and an ordinary barometer showed that as the pressure increases the radiation at a given spot always diminishes slightly (provided no big temperature change occurs). This phenomenon, called the barometer effect, may be understood simply if the source of the mysterious radiation is beyond the limits of the earth's atmosphere. Indeed, a rise in atmospheric pressure of, say, one centimetre of mercury amounts, in this case, to a corresponding increase in the weight of air over the observer of 13.6 grams per square centimetre of surface.

The inevitable conclusion to be drawn from the above-mentioned experiments was that the unknown rays were of extraterrestrial origin. To emphasize that the source of these rays was to be sought somewhere in the cosmos beyond the earth, they were called *cosmic rays.*

But from this first conclusion there inevitably followed also the conclusion that this radiation possessed unthinkable penetrating power as compared to all previously discovered radiations.

One must only take into account that ionizing radiation is not by any means absorbed in the same way as is the sun's visible light, which easily penetrates the thick layer of atmosphere that blankets the earth. Visible light rays carry too little energy to break up the molecules of the majority of substances into ions. Therefore, the energy expended by these rays as they pass through a substance is comparatively small so that even such dense substances as glass (to say nothing of gases, and among them the air) may prove very transparent to visible rays.

The situation is quite different in the case of such invisible rays as X-rays and gamma rays; since their energy exceeds by thousands of times the energy of visible light rays, they interact with matter much more strongly, for example, by ionization of substances; consequently, also the energy loss of radiation in matter proceeds much more rapidly. These rays are absorbed perceptibly even in metre thicknesses of air.

This fact has also been confirmed many times in studies of the absorption of cosmic rays in widely different substances.

It was found, for example, that a centimetre thickness of iron absorbed ionizing rays almost in the same way as an equal (in weight) layer of air (70 m.), though the transparency of iron and the transparency of air to visible light cannot be compared. If we recall, however, that the most energetic of the earlier known rays, gamma rays, are very strongly absorbed already in a layer of air several tens of metres in thickness, then the very fact that cosmic rays pass through many kilometres of the earth's atmosphere compelled physicists from the outset to ascribe to these rays energies exceeding those of the most penetrating known gamma rays by tens of thousands of times. This fact, it

would seem, permitted scientists to cease once and for all any attempts to put cosmic rays on a level with the charged alpha and beta particles of radioactive substances, inasmuch as the penetrating power of the latter is many times less than that of even the gamma rays.

The investigations of Mysovsky, Millikan, and others mark the end of the first, and, in a sense, preliminary stage of the study of cosmic rays. As we shall see later on, the guesses made by Millikan and other workers concerning the properties of this radiation proved erroneous, but its cosmic origin is now established irrefutably. Likewise, the instruments used at that time now seem far from perfect; as we shall show in Chapter II, instruments were soon to appear that gave much more accurate and vivid data concerning cosmic rays. And yet we shall never forget the work done by the pioneers of cosmic ray investigations, for their modest attainments were made through titanic labour and often at the risk of their lives. No small part was played here by Soviet scientists who were stopped by no obstacles in pursuit of their aims. Such was the work of professor Verigo who made his measurements in a submarine at depths up to 40 m., on the glaciers of Mt. Elbrus and in the stratosphere. Here also belongs the world-famous flight of Prokofiev, Birnbaum and Godunov who in 1933 registered cosmic rays directly in the U.S.S.R.-1 stratostat in an ascent to 19 kilometres above sea level.

Chapter II

HOW IS IT POSSIBLE TO SEE AN INVISIBLE RAY?

As we all know, in addition to visible light rays there exist many other radiations of different kinds: radio waves, heat (infrared) rays, ultraviolet rays, and so forth. Each type of radiation affects the human body in its own way, and some types cannot be detected at all without special instruments.

However, from the viewpoint of the physicist, the ability of radiation to act on the various sense organs is not a property of prime importance. To determine the nature of the radiation it is far more important to know how it propagates and how it interacts with matter.

Despite the peculiarities of each type of rays, there is one thing they have in common: they all propagate in space much as do waves on the surface of a body of water. The difference here, however, is that in place of oscillations of the particles of the liquid we find periodic alterations in the magnitude of electric and magnetic fields, and the presence of matter is by no means essential. For this reason, all the above-mentioned rays are designated by the generic term "electromagnetic waves."

The properties of each type of wave are determined by the wave length, that is, the distance between adjacent wave crests (Fig. 5). The shorter the wave and the higher

the frequency of oscillations of the field, the greater the energy conveyed by the propagating wave. An electromagnetic wave may interact with matter and transfer to it a part of its energy, in which case there take place phenomena such as emission of electrons from a metallic surface

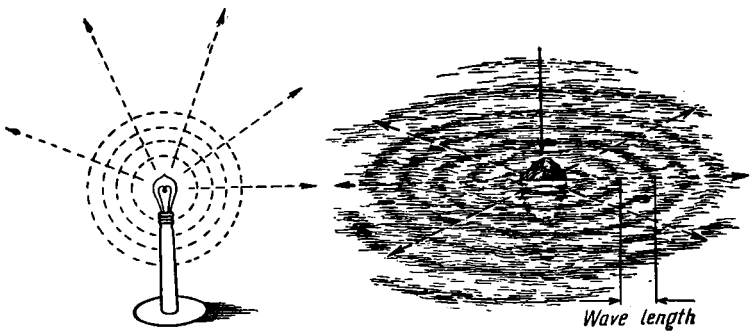


Fig. 5. The propagation of light from a lamp very much resembles the waves that arise when a stone falls on a surface of water. The distance between two adjacent wave crests is called the wave length. (The wave lengths of visible light are of the order of several ten-thousandths of a millimetre.)

irradiated by light (the so-called photoelectric effect), ionization of the air, and so forth. It is precisely these properties, in addition to a great penetrating power, that Millikan had in view when he spoke of the newly discovered rays of nonterrestrial origin as electromagnetic rays of exceptionally short wave length, and, consequently, of very high energy.

To study cosmic radiation it was necessary to work out methods of registering it, to find ways not only of detecting the presence of the new invisible rays but also to investigate them qualitatively and quantitatively.

THE FIRST METHOD OF REGISTERING INVISIBLE RAYS

Registration of rays is done by instruments that make use of the specific properties of the given radiation. Thus, for example, X-rays may cause fluorescence of certain substances, and therefore screens covered with films of such substances enable us to "see" X-rays, or, to be more exact, to evaluate with the naked eye their presence and intensity by the brightness of fluorescence. Radio waves are capable of causing in conductors rapidly alternating electric currents which are easily registered by radio receiving sets.

However, nearly all electromagnetic waves (both visible and invisible) possess one property in common, which is very apparent in the case of high-energy waves. This property consists in the ability to ionize the molecules of a substance, i.e., to knock out of them the lightest charges, electrons.

Therefore, the simplest measure of the intensity of invisible high-energy radiation is the quantity of ions constantly being formed in the air due to the action of these rays. This very simple principle was the basis for registration of cosmic rays already in the first experiments of Kolhörster, Mysovsky and other investigators working with electrometers.

The fibres of a charged electrometer, as shown in Fig. 6, are similar to the leaves of a simple electroscope (see Fig. 2); under the action of ionizing rays they gradually lose their charge and return to their original unbent position. This is because the electric charges which originate in the air due to cosmic rays accumulate on the fibres of the electrometer and are neutralized there by charges of opposite sign. Thus the rate of discharge of the electrometer is a measure of the intensity of cosmic radiation.

Later, the electrometer method was considerably improved. The operating volume of air where ionization of molecules takes place was separated from the registering part

of the instrument and enlarged many times; the result was a so-called *ionization chamber* connected only electrically with an electrometer and designed to collect large numbers of electrons and positive ions that originate in the chamber. Further, in order to raise the effectiveness of the chamber,

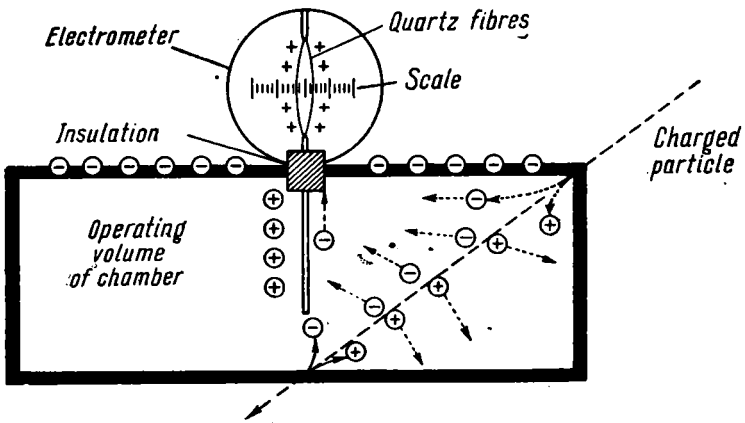


Fig.. 6. Registration of invisible rays by an electrometer and ionization chamber is based on the ionization of the air in the large volume of the chamber

the quantity of air or other gas was increased by raising the pressure to several tens of atmospheres. Finally, the deflection of the fibre of the electrometer was fixed by a reflection of light (Fig. 7.), the position of which was registered by a motion picture camera, the latter being regulated by a clockwork mechanism. This was how, for example, the first self-registering instruments were made that were taken in sounding balloons to high altitudes, or, on the contrary, underwater to great depths.

Although the ionization chamber is widely used at present in the study of cosmic rays, still in itself it gives but little for an understanding of the nature and properties of cosmic radiation. First of all, an ionization chamber cannot tell us whether we are dealing with "genuine" electromagnetic waves of the gamma ray type or not, since fast

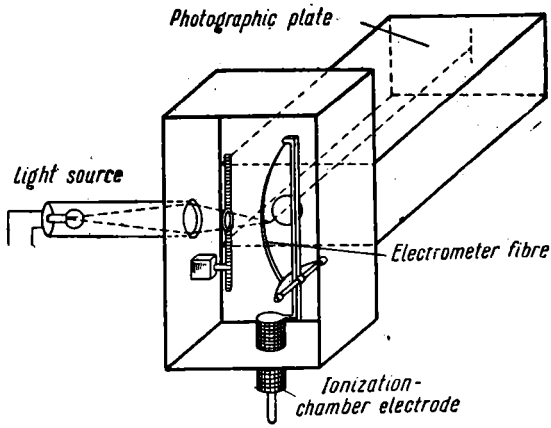


Fig. 7. An electrometer connected electrically with an ionization chamber. The deflection of the fibre of the electrometer is photographed

electrically charged particles, such as the alpha and beta particles of radioactive substances, can produce in a gas not fewer but many times more ions than even very high-energy rays.

A FOG THAT HELPS US TO SEE

As early as 1911, the English physicist Wilson proposed an entirely new method for registration of charged particles (the alpha and beta particles of radioactive substances). Instruments based on this method enable us to "see" particles of the microcosmos despite their dimensions that are hundreds of millions of times smaller than what can be seen in the most powerful optical microscope, and despite their velocities that exceed those of a bullet hundreds of thousands of times.

Strange as it may seem, the principle of the new instrument, called the *Wilson cloud chamber* after its inventor, was the result of a many-year study of rains and fogs. How do clouds collect in a clear sky and why does rain fall? It

is common knowledge that the most transparent air always contains a greater or lesser quantity of moisture due to evaporation from seas, lakes and rivers. The moisture, water vapour to be more precise, is not noticeable because the individual molecules of vapour are uniformly distributed in the air and do not disturb its homogeneity (for the same reason an aqueous solution of sugar is transparent). But when atmospheric pressure falls the vapour becomes supersaturated and the individual molecules of water begin to join into tiny droplets that in turn combine to form large drops; the big heavy drops are no longer able to flow freely in the air and therefore fall. But, it appears that for condensation of such supersaturated vapour to take place, so-called centres of condensation in the air are necessary. It is precisely around such centres that the formation of droplets of water begins. And on the contrary, if such centres of condensation are lacking the molecules of vapour cannot combine to form drops even if there is a great excess of them. In the atmospheric air, the centres of condensation are usually dust particles, especially if they carry electric charges, as we find in storm clouds. This is why special guns that fire sand into the clouds have sometimes been used to bring about artificial rain.

Wilson's idea was to produce something like artificial rain or fog with the aid of charged particles. In its simplest form, his instrument consisted of a cylindrical glass chamber with a piston in place of the bottom (Fig. 8). Inside the chamber was water vapour. By suddenly pulling out the piston, the pressure and temperature of the air in the chamber could be reduced and an excess of moisture created, i.e., a state of supersaturated vapour. If the air in the chamber has been carefully cleared of all admixtures, the molecules of vapour will have nothing to condense on and the air in the chamber will remain absolutely transparent. Now what will happen if at this moment a fast-moving charged particle passes through the chamber? In its traverse such a particle will break up the molecules of the air

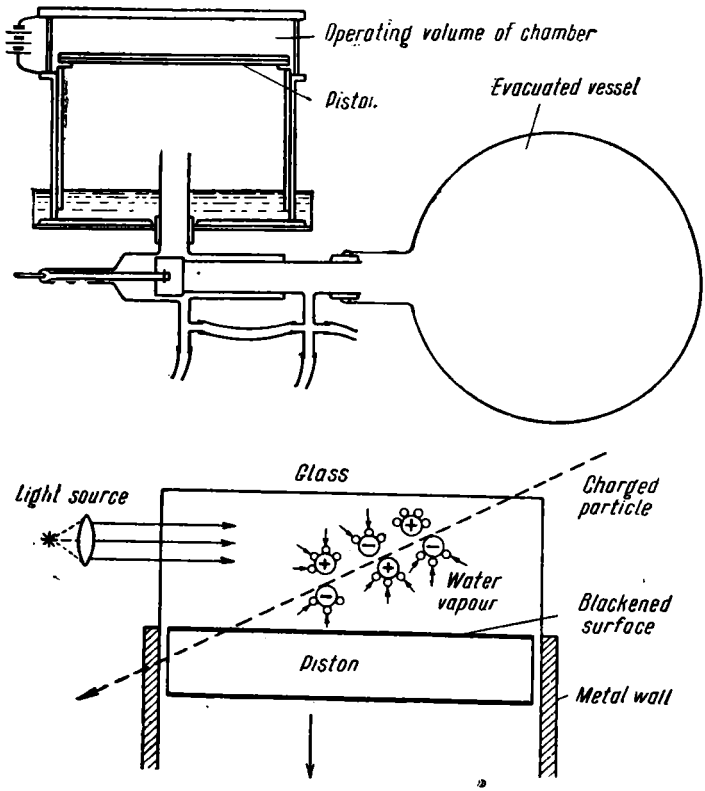


Fig. 8. The construction of Wilson's chamber and how it works. Ions are left in the wake of a charged particle as it passes through the chamber; molecules of vapour condense on the ions when the pressure and temperature fall, and thus form a track

into ions, creating in this way charged centres of condensation.* Wilson's experiments showed that the molecules of a liquid precipitate very well on such ions, producing tiny individual droplets easily seen in a microscope and dis-

* Hence, from the principle according to which the Wilson chamber operates it might be called a condensation chamber to distinguish it from the simple ionization chamber.

persed more or less densely along the path traversed by the particle in the chamber (Fig. 9). Such a track will be especially visible if we direct a strong beam of light into the chamber from the side and view the inside of the chamber from the front, on the background of the piston, which has a special coat of black paint. Immediately after the track has been observed, the piston must be returned to its original position and an electric potential of the order of 100 to 200 volts applied between the walls of the chamber and the piston. This will rapidly pull back to the walls the ions together with the drops of liquid. Several seconds later, when the air in the chamber has heated to the surrounding temperature it will be ready to register a second charged particle.

In time, this instrument, which was rather simple in principle but comparatively "finicky" in operation, underwent considerable refinements and was made more auto-

Fig. 9. The track of a charged particle in a cloud chamber greatly magnified. The photograph shows two little chains of droplets of the liquid that have condensed on the ions. Ions of opposite sign are separated by an electric field that sweeps them out of the volume of the chamber

matic, thus making the modern Wilson cloud chamber a tool for very detailed and visual studies of cosmic rays.

First of all, a camera was used to record everything that took place inside the chamber. It took a fast picture immediately after the piston had been pulled out following the formation of tracks in the chamber. Usually, the photographs are taken with two objectives. This produces a three-dimensional picture (just as our vision with two eyes) and not a two-dimensional flat picture of the passage of particles through the chamber.

A photograph made in a cloud chamber can give numerous valuable data. The density of the track (the number of droplets per centimetre of path) enables us to calculate, using appropriate equations, the speed of the particle that produced the track (the slower the charged particle, the greater the number of molecules it succeeds in ionizing over each centimetre of its path). The length of the track, provided it ends within the chamber, enables us to compute the total number of ions produced by the charged particle. If we know the energy required to break up one molecule of gas into ions, it is possible to calculate the total energy that the particle originally possessed before dissipating it on ionization of the gas.

In 1927, the well-known Soviet physicist and now Academician, D. V. Skobeltsyn, was the first to use the Wilson chamber in the study of cosmic rays. Earlier he had used a chamber placed in a magnetic field to study the properties of charged particles emanating from radioactive sources. This method proved extremely effective. The path of a charged particle in such a chamber is curved from a straight line into the arc of a circle.

We know that a magnetic field deflects moving electric charges. The faster the charged particle moves and the greater its mass, the less it is affected by the magnetic field. This is clearly illustrated in Fig. 10. The photograph shows the tracks of two particles, one of which moved fast and left nearly a straight track; the other, slower particle,

moved in a strongly curved trajectory. Other conditions being equal, particles of unlike sign are deflected by a magnetic field in opposite directions. This enables us to determine the sign of the charge just by looking at the trajectory of the particle. By measuring the curvature of the track of the particle in a given magnetic field, it is possible, using very simple equations, to determine the momentum of the particle, that is, the product of its mass and velocity. Now if the mass of the particle has been found from other data, its velocity and energy are thus determined. The energy of charged particles is usually measured in so-called electron volts. An electron volt is the energy gained by a particle having one electronic charge when it passes through a potential difference of one volt.

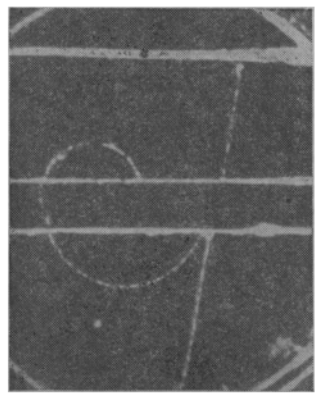


Fig. 10. The tracks of charged particles in a cloud chamber placed between the poles of a magnet. Two particles emerge from one point in a lead plate inside the chamber. They differ greatly as to speed: the slower particle moves in circles, while the fast particle is hardly at all deflected

Skobeltsyn's method was of great importance in studying the nature of cosmic rays. Below we shall see how it was used to discover in cosmic radiation particles of "terrestrial" matter so well known to physicists, and also to discover new, hitherto unknown, particles. Here we shall only note that already in 1927 Skobeltsyn was the first in the world to observe in a cloud chamber charged particles not connected with radioactive substances. In contrast to alpha and beta particles, the magnetic field, it appeared, did not in the least deflect these particles, and this meant that their velocity and energy were extraordinarily great. Skobeltsyn published the

results of his unexpected observations and drew the bold conclusion that the stupendous penetrating power of cosmic rays may be due, at least in part, to these very high-speed charged particles. Investigations that followed indicated that that was the path to follow in seeking to solve the riddle of the cosmic rays.

CAN INDIVIDUAL ELECTRONS BE COUNTED?

As we have seen, the principle of the ionization chamber consists in the collecting of electric charges that are left behind by rays or fast charged particles passing through it. The positive ions move in one direction and the negative ions in the opposite. The net charge in this case is usually so negligible that only a continuous passage of cosmic rays through the chamber results in the accumulation of a charge that can be measured directly.

Now the question arises: Is it not possible in some way to register even the very smallest "portions" of cosmic radiation instead of determining merely an average intensity of this radiation over a definite and rather long period of time?

Among the solutions of this problem, one consisted in using an instrument proposed as early as 1913 by the physicist Geiger. For an explanation of how this instrument works let us digress for a moment into the field of electric discharges in gases. If a sufficiently large voltage (in the neighbourhood of several thousands of volts) is applied between a metal point and another electrode, that is, a metal object of any shape, and if this voltage is gradually increased, at a certain moment a spark will jump across the gap between the electrodes. What is a spark? It is a stream of electric charges accelerated by a big electric potential; when these charges encounter molecules of air they break up a portion of them into ions and impart to others a certain excess energy which is later released in the form of light. To convince yourself that a spark is really a stream of charges,

connect an ammeter in an electric circuit with a spark gap; when a spark jumps across the gap the needle of the ammeter gives a sharp jerk. Each one of the ions newly formed in the spark develops sufficient speed to be capable of ionizing fresh molecules of gas; it is enough at first to have only a few charges in order to form a whole avalanche of ions moving at high speed towards the point (Fig. 11).

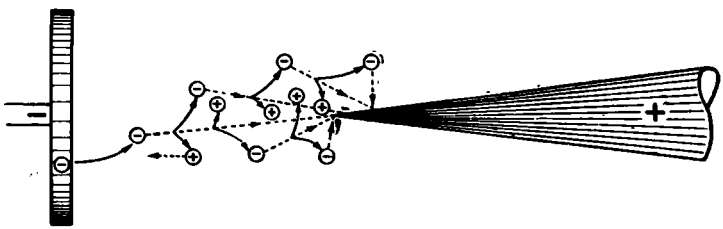


Fig. 11. This is how a spark arises between two electrodes

The instrument suggested by Geiger consisted of a metal vessel inside of which was a point carefully insulated from the body of the vessel. A very strong electric field was created near the point due to the high potential between the point and the body. If a charged particle of sufficient energy entered such an instrument, it ionized the molecules of air, and if this occurred near the point, that is, in the vicinity of the strong electric field, a whole avalanche of electric charges was formed in the vessel, producing something in the nature of a spark.

Thus, in contrast to the ionization chamber, Geiger's instrument was able to register individual charged particles, such as alpha and beta particles.

Later, already in 1924, Geiger, working together with Müller, another physicist, greatly improved on his instrument. The point was replaced by a fine metal axial wire the length of the glass or metal cylinder (Fig. 12). A big negative voltage is applied to the metal body or the inside surface of the glass cylinder which is coated with a material that conducts electricity (this part of the counter is

called the cathode). The fine wire, which is charged positively with respect to the cylinder, creates about itself (in the same way as the point) a strong electric field capable of accelerating to a high speed the free electrons that appear around the wire. In this case, the operating volume of the counter is expanded appreciably since nearly every electron that appears within the cylinder as a result of ioni-

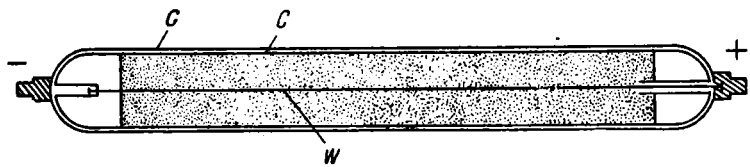


Fig. 12. A modern Geiger-Müller counter (one of many designs). *G* is the glass body, *C*—the cathode in the form of a conducting layer deposited on the inside of the glass. A negative potential is applied to this layer. *W* is a wire charged positively with respect to the cathode. About the wire is formed a strong electric field

zation of the air must finally land in the vicinity of the strong field near the wire, no matter from what direction it comes. The pressure of the gas in the counter was reduced to roughly one-hundredth of atmospheric (or several centimetres of mercury); this produces a silent, so-called corona, discharge in place of the spark discharge which ceases just as rapidly as a spark, due to the large voltage drop in the electric circuit at the very first instant of discharge.

Later, the counters were filled with special mixtures of gases to stop the electric discharge irrespective of the external voltage and considerably reduce the time required to prepare the counter for registration of the next particle. They came to be known as high-speed or self-quenching counters (to distinguish them from the original Geiger-Müller counter) and are capable of recording several thousand particles per second.

And that is not all. It was found that special electron-

ic circuits could be used to amplify greatly the leaps or, as they are commonly called, pulses of voltage on the counter caused by the discharges. The amplified electric pulses are conveniently recorded by a special relay called a mechanical counter or numerator.

A radically new technique in the use of counters was proposed in 1929 by the German physicists Bothe and Kol-

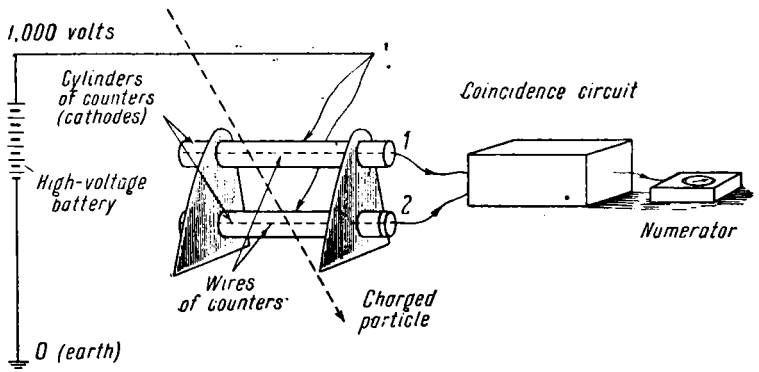


Fig. 13. An arrangement of a simple "telescope," the purpose of which is to register particles arriving in a given direction. Coincidence of discharges in counters *1* and *2* is recorded by an electronic circuit that triggers a numerator

hörster. They placed several counters one above the other so that the wires were parallel, as shown in Fig. 13. If the pulses from all these counters are conveyed to an amplifying unit of special design that triggers the numerator only when the pulses on all counters are simultaneous (the so-called coincidence method), the apparatus will then register only those particles which pass through the whole system of counters. Just as an astronomical telescope can observe the stars only in a small portion of the sky at one time this device, which is also called a "telescope," enables one to determine rather accurately the direction from which the charged particles arrive.

In 1933, Blackett and Occhialini (in England) used a "telescope" of counters together with a cloud chamber. One

of the counters was placed above the chamber and the other below it, as shown in Fig. 14. Through the use of a special electric arrangement, the chamber operated only from coincident discharges of both counters. In other words, the

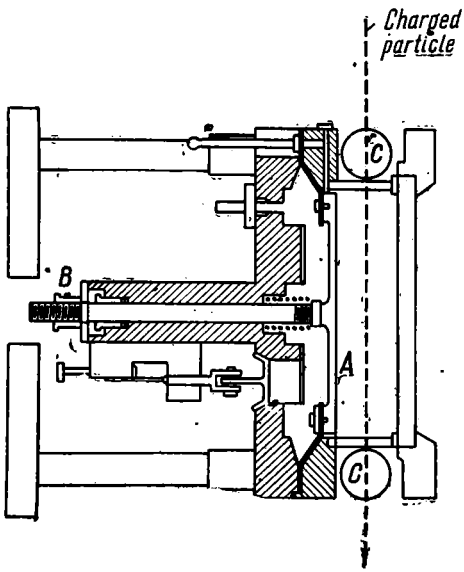


Fig. 14. A controlled cloud chamber. Simultaneous discharges of both counters *C* trigger the piston of the chamber and the camera. *A* is the piston of the chamber and *B* the electromagnetic relay

air in the chamber was expanded and the shutter of the camera triggered only when a charged particle passed through both counters and, consequently, also through the chamber between them. Whereas formerly only several in a hundred photographs taken at random exhibited the tracks of fast charged particles, now over a half of the photographs displayed the track of such a particle. This meant that material for studying the properties of cosmic radiation began to accumulate dozens of times faster than before.

PHOTOGRAPHY WITHOUT A CAMERA

We have already described how charged particles are "photographed" by illuminating their tracks in a cloud chamber using very bright, but nevertheless ordinary light.

But even before the discovery of cosmic rays it was known that rays invisible to the naked eye act on photographic plates not worse, but often better than visible rays. It was these photographic plates wrapped tightly in black paper that were first used in experiments to detect X-rays and gamma rays. If such is the case, why not try the effect of cosmic rays on the light-sensitive emulsion of a photographic plate?

Anyone with a knowledge of photographic processes could expect such an attempt to be successful. Silver bromide is a common constituent of light-sensitive emulsions. It is contained in the form of very small individual grains in a thin layer of a transparent mass (gelatine) deposited on the plate. When in a chemical compound with bromine, the silver does not display all its specific properties, including colour: the grains of silver bromide are completely transparent. The chemical bond between the atoms of bromine and silver, as in any molecule, is due to purely electric forces: one of the electrons of an atom of silver is firmly attached to an atom of bromine. When a photographic plate is illuminated by ordinary light, these binding electrons are knocked out of the crystal of silver bromide, and the atoms of pure silver are freed; they are the ones that create the characteristic darkening of the plate. Obviously, if these same electrons are knocked out of the silver bromine by electrically charged particles the effect will be the same. A process of this type may easily be visualized from Fig. 15.

Experiments had long since been showing that the heaviest particles as, for example, alpha particles, are capable of leaving a so-called "latent image" of their tracks on

a photographic plate. Using a microscope after the plate has been developed, one can easily detect inside the plate a tiny chain of dark specks on a background of transparent emulsion.

It is not hard to figure out that the length of such a chain of developed emulsion grains will be proportional to the initial energy of the given charged particle. Computations have shown that for an alpha particle emitted by radioac-

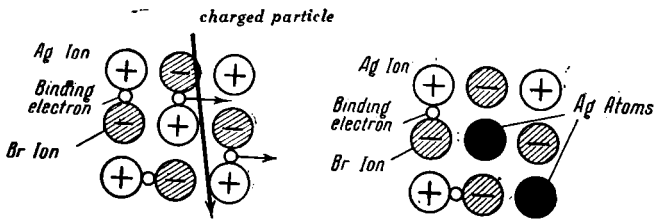


Fig. 15. The action of an energetic, but not very fast, charged particle on a grain of silver bromide in a photographic emulsion: the detachment of a valence electron disrupts the connection between the silver ions (Ag) and the bromine ions (Br); the silver is deposited in the form of atoms causing the emulsion, finally, to darken

tive substances, the length, should be approximately 50 microns (0.05 mm.), and therefore such a chain cannot fully fit into a layer of emulsion that is only 20 microns thick in ordinary plates. Mysovsky was the first to suggest making thicker plates; and already in 1928 he actually obtained tracks of alpha particles on them. Several years later the technique of preparing such thick emulsion plates was considerably improved by one of Mysovsky's pupils, A. Zhdanov, who in 1934 was the first to use these plates for photographing cosmic particles. One such photograph is shown in Fig. 16. As we have already pointed out, the greater the ionizing power of the particle, the more apparent will be the track of the charged particle in the photographic emulsion. To be able to do this, the particle must move slowly and at the same time have a large supply of energy,

that is, it must be sufficiently "massive." For this reason, only the heavier particles, chiefly fragments of atomic nuclei, protons (and only such as have a small speed), could be studied in Zhdanov's experiments.

If we leave out the time- and labour-consuming work of preparing, developing and examining microscopically the developed plates, the new method of registration, or, if you will, photography of cosmic particles, is extremely simple. But the exposure must be very great because the number of cosmic particles entering the plate is extremely small: not more than 1.5 cosmic particles of all types (at sea level) hit each square centimetre of plate per minute; and usually only about one-thousandth of this number have a sufficiently slow speed. To photograph cosmic rays, one must leave at the desired altitude a packet of thick emulsion plates wrapped in black paper (for protection from visible light) for a more or less long period of time (something like half a month) so that a sufficient number of tracks can accumulate in the emulsion, and likewise so that the very first tracks should still be developable. Then the cosmic particles (which in the majority of cases move vertically) and above all the slowest particles, should "photograph" them-

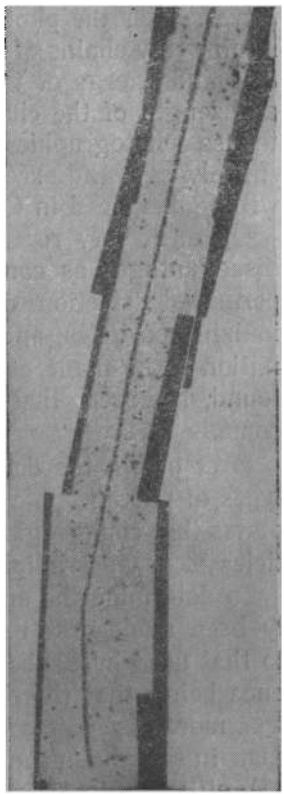


Fig. 16. A characteristic track of a heavy charged particle (proton) in a thick photographic emulsion

selves. After the photographic plate has been developed, it retains tiny chains of dark specks; one may judge of the nature and energy of the "snapped" particles by the density and length of the chains. A. Zhdanov was one of the first to use photographic plates in the investigations of an entirely new and exceedingly important phenomenon which will be described in Chapter V.

Up until very recently photographic plates had two big disadvantages as compared with the cloud chamber: they permitted detection only of relatively slow and heavily ionizing particles, and, as a rule, did not enable a determination to be made of the energy of these particles. It was found, however, that both disadvantages could be overcome.

First of all, the development of new and more sensitive types of photographic emulsion made it possible to produce plates that could register even the most thinly ionizing particles of cosmic radiation.

To determine the energy of the particles, use has recently been made of a method of magnetic deflection, similar to that used by Skobeltsyn for the cloud chamber, the difference being that the deflecting action of the magnetic field was more easily detected in the air gap between two plates than in the photographic plate itself.

A still more effective and also simpler (in principle) method consists in utilizing the deflecting action of electric fields. There is no necessity of creating these fields artificially, since, as we know, the atomic nuclei of the matter of an emulsion are surrounded by strong electric fields that are not extensive but exceed by many times the strength of fields ordinarily met with in engineering practice.

In recent years a procedure has been elaborated and checked that enables the random, at first glance, deflections experienced by particles colliding with atomic nuclei in the photographic plate to be used to determine the energies

of the charged particles. As a result, photographic plates have now become just as effective as the cloud chamber, and in a number of cases they afford even a more vivid means of investigating charged cosmic particles. One of their advantages is that they operate continuously: unlike the cloud chamber, a photographic plate is ready at any moment to create a "latent image" of the track of a charged particle passing through it.

The photographic plate method had other disadvantages. First of all, a relatively thin layer of emulsion (up to 1,000 microns) contains a relatively small number of atomic nuclei and, in general, matter. This greatly limits the possibility of studying transformations that occur in the substance of the emulsion due to the action of cosmic rays. Furthermore, the chemical composition of an emulsion is rather complex; it includes a whole "set" of the most diverse types of atomic nuclei. For this reason, it is difficult to say what the target is in concrete instances when a cosmic particle impinges on a nucleus.

To overcome the first disadvantage, physicists began to manufacture so-called "stacks of stripped emulsion." The principle behind this method consists in obtaining a large number of individual and relatively thin emulsion layers not on glass but in the form of sufficiently firm films, which can then be placed one on top of the other like a stack of "pancakes."

Modern laboratories use this method to make round and square stacks 10 and more centimetres thick with the total volume of continuous emulsion of the order of several litres. The result is a sort of "emulsion chamber," which after irradiation by cosmic rays may again be divided into individual layers to facilitate further treatment.

The second disadvantage (nonhomogeneity in the chemical composition of the emulsion) is not so easy to overcome. Different laboratories have made repeated attempts to introduce into the emulsion tiny balls, thin wires, or foils of the substance to be investigated. However, the total mass

of all these inclusions remains small in comparison with the mass of the entire emulsion, and this means that the number of "direct" hits of cosmic particles on atomic nuclei of a known type is not great. This is why the photographic emulsion method, despite its quality of vividness, has to be supplemented by experiments with cloud chambers into which any substance we are interested in may be introduced either in the form of a gas or a solid plate put across the chamber.

Chapter III

RAYS OR PARTICLES OF MATTER?

MILLIKAN'S HYPOTHESIS QUESTIONED

As has been pointed out above, the first investigators of cosmic rays, and especially Millikan, believed them to be very similar to radioactive gamma rays. And it would seem that such a concept is supported by weighty evidence connected with the properties of radioactive radiations in general. Indeed, gamma rays, which are electromagnetic waves, are very much more penetrating than alpha or beta rays, which consist of high-speed charged particles.

The reason for this advantage of gamma rays also seemed very natural, since charged particles of sufficiently high energy quickly fritter away this energy in their movement through matter by constant encounters with other atoms (or molecules) and by knocking electrons out of the latter. On the other hand, when electromagnetic waves pass through the very same substance, they rarely shuckle off electrons from the atoms and thus spend their energy more "economically." To be convinced, one only needs to place sources of different radioactive radiations in a cloud chamber: the tracks of all alpha and beta particles will be seen as a large number of continuous foggy lines emanating from the source of the particles, whereas a source of gamma rays will create throughout the volume of the chamber only isolated "branchlets"—the tracks of electrons jerked out of the atoms of gas by an electromagnetic wave.

However, Skobeltsyn's first experiments with a cloud chamber in a magnetic field showed that in cosmic rays the problem was more complicated. Skobeltsyn placed a source of gamma rays near the chamber and observed in it tracks curved by the magnetic field into tiny thin ringlets; these were the tracks of the electrons torn out of the gas atoms by an electromagnetic wave. When the source of gamma rays was removed, no ringlets were obtained, but at times the chamber was pierced by the same thin yet almost ideally straight lines. And what is more, Skobeltsyn later noticed that sometimes several such tracks appeared at once emerging from the walls of the chamber in the form of a slightly expanding beam (Fig. 17). Such beams or streams were soon called "showers" from their similarity to what is commonly observed when an oblique driving rain hits a window-pane. The cause of such showers in the cloud chamber was far from understood at that time. However, the rectilinear character of the tracks, which obviously were due to the action of cosmic rays, pointed to the unquestionable presence of charged particles of very high energy. In order to escape the deflecting action of the magnetic field this energy had to exceed that of the ordinary beta particles of radium by no less than several hundred times.

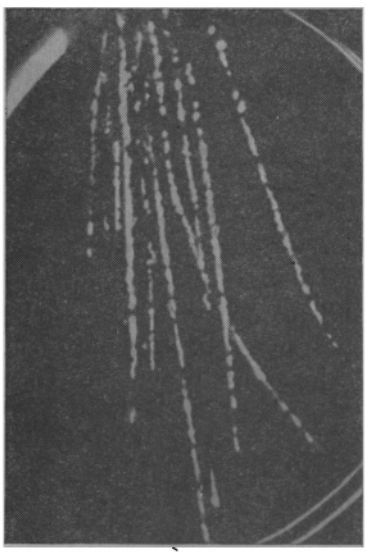


Fig. 17. A "shower" of cosmic particles photographed in a cloud chamber

This same conclusion was also soon obtained in experiments with counters. In using a "telescope" to register

charged particles not connected with any radioactive sources, physicists began to insert massive layers of different substances between the counters of the "telescope." It was then found that a 4 cm. gold shield weighing about 80 g. per sq. cm. reduces the number of registered particles only by 2.5%.

If we recall that the ordinary beta particles of radium are absorbed completely even by a millimetre plate of light aluminium, the stupendous energy of the charged particles present in cosmic radiation once again becomes apparent. It was hard to believe that they were all electrons dislodged from atoms of matter by some sort of gamma rays of cosmic origin. On the other hand, the following question was entirely justified: Could it be that all these high-energy particles arrive directly from cosmic space and penetrate the entire layer of the earth's atmosphere?

However, in spite of all doubts, Millikan's hypothesis could not be fittingly verified until the observer got out beyond the earth's atmosphere, for it might be that the superpower gamma rays arriving from cosmic space produced in the atmosphere all the charged particles that are actually observed.

THE GLOBE HELPS IN MEASUREMENTS

And so to solve the problem of the nature of cosmic rays it was necessary to begin storming the heights of the atmosphere. If it were possible to send up measuring equipment nearly to the top of the earth's atmosphere it might be possible to dismiss the influence of the atmosphere and study the cosmic rays almost in the "pure" state. The problem was an exceedingly difficult one.

One of the first to solve the difficult problem of cosmic ray investigation in the upper layers of the atmosphere was the Soviet physicist S. Vernov. In 1934, he constructed an automatic portable apparatus for registration of cosmic rays. It was carried up into the stratosphere by small bal-

loons to an altitude of 25 to 28 km. (Fig. 18). The equipment was fully automatic: all instrument readings including the barograph readings of the altitude were continuously transmitted back to earth by radio. It may be mentioned here that transmission of data by radio was mastered in the laboratories of other countries only several years later.

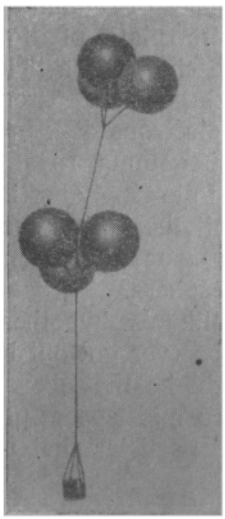


Fig. 18. Automatic equipment in flight

What instruments had to be sent into the stratosphere to determine the composition of cosmic rays? The ideal thing would of course be a cloud chamber, and still better, one with a magnetic field around it. But it was out of the question to think of sending up by pilot balloon such a ponderous and rather "finicky" instrument. It was found that such an instrument was not even necessary since it could be replaced by an ordinary electrometer or by counters.

And nature "produced" the magnetic field, for the earth taken as a whole is really a gigantic magnet. It is surrounded by a relatively weak magnetic field which, however, extends out into space many thousands of kilometres from the surface of the earth. Only the presence of the earth's magnetic field could explain the interesting fact established at that time concerning the varying intensity of cosmic rays at different latitudes of the earth's surface: it diminishes slightly in the direction from the poles to the equator. Indeed, at the magnetic poles where the cosmic rays move to earth along the lines of force (Fig. 19), even charged particles should not experience any deflection; near the equator where the cosmic rays move earthward across the lines of force, the deflection effect of the magnetic field

should be a maximum, and the slowest charged particles should not be able to "break through" even to the atmosphere, to say nothing of the earth's surface. By conducting investigations of cosmic rays in the stratosphere it might be hoped to find out how charged particles, whose trajectories are curved by the deflecting action of the earth's magnetic field, gradually disappear from the "field of view" of the observer as he moves towards equatorial latitudes. These are particles which, due to their relatively slight energy, are sufficiently sensitive to the earth's magnetic field and are likewise not able, in the majority of cases, to penetrate the earth's atmosphere to sea level.

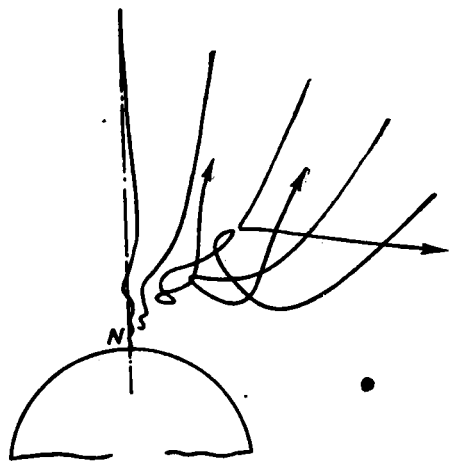


Fig. 19. The action of the magnetic field of the earth on charged primary particles. If the cosmic rays were electromagnetic waves they would not be deflected by the magnetic field and their intensity would be the same at all points on the globe. *N* is the North Magnetic Pole of the earth

Such was the logic that led Vernov to decide to organize an equatorial expedition. The Soviet motorship "Sergo" left Odessa for Vladivostok via the Indian Ocean in 1937 with the necessary instruments and a supply of bladders for balloons.

The members of the expedition did a brilliant piece of work in carrying out the planned programme of investigations and attained exceedingly important results: cosmic ray intensity in the stratosphere over the equator proved to be nearly a quarter of that at the latitude of Leningrad.

There were no longer any doubts: cosmic rays were unquestionably a stream of charged particles that are affected by the deflecting action of the earth's magnetic field.

Only the very high-speed particles are able to "break through" the magnetic field of the earth at any latitude. However, those particles which reach the earth at remote distances from the equator also possess sufficiently high energies. Special computations that take strict account of the deflecting action of the earth's magnetic field show these energies to be of the order of thousands of millions of electron volts! This means that the majority of charged particles of cosmic radiation have energies a thousand times greater than that of particles from radioactive substances, though the latter so recently appeared to physicists as the very limit for the known velocities of particles of matter.

Thus Vernov, and also Millikan, and later other physicists, proved, by using the earth's magnetic field, that cosmic rays are not electromagnetic waves but charged particles with enormous energies.

From that time, the term "cosmic rays" lost its original meaning. However, it should be noted at this point that the difference between rays in the ordinary sense of the word and streams of particles of matter is not so great as was earlier thought.

The fact is that as far back as the end of the nineteenth century a study was made of an extremely curious phenomenon, that of the emission of electric charges from metal under the action of light. A study of the laws involved (it was called the photoelectric effect) as well as of other properties of radiation showed that different types of radiation behave as streams of minute particles, known as photons.

Each type of radiation is characterized by photons of a strictly definite energy. The shorter the waves of electromagnetic radiation the more energy do the photons of this radiation possess. Each photon is capable of being absorbed by an atom of matter, in which case it gives up its ener-

gy to the atom, and one electron of corresponding energy is ejected. Using this effect as a basis, it was very easy to explain both the photoelectric effect and the ability of different radiations to ionize gas.

Numerous experiments showed that photons, like particles of matter, possess a mass that is computed by dividing the energy of the photon by the square of the speed of light. It then became possible, in a certain sense, to correlate particles of radiation (photons) and particles of matter. True, there still does exist an essential difference between particles of matter and photons. It is this: photons of a given type have an energy and a mass that are always constant and are *due wholly to motion*; in the case of a particle of matter, the mass increases with the velocity, but even in a state of relative rest the particle possesses a certain mass, called the *rest mass,* and this latter is the distinguishing feature of particles of a given type of matter, electrons, protons, and so forth.

When we speak of the mass of a particle we usually have in mind the rest mass, that is, mass in the narrower sense of the word. In the case of photons the rest mass is altogether absent.

Chapter IV

CASCADES IN LEAD AND AIR

THE "BIRTH" AND "DEATH" OF A POSITIVE ELECTRON

Some 20 years ago physicists believed matter to be constituted in the following simple manner. It consists of individual molecules. Despite the enormous number of substances known to science, and, hence, the different types of molecules, the latter are all made up of combinations of an extremely small number of the atoms of elements, these simplest substances that are chemically indivisible. Nature knows of ninety-two such elements.* Each atom in its turn is a combination of only two types of elementary particles—electrons and protons. These bits of electricity were believed to be the sole, eternal and immutable "building blocks of the universe" as was once the atom. In principle, it seemed sufficient to know the basic laws of mechanics supplemented by the basic laws of electromagnetic interaction of positively charged protons and negatively charged electrons in order to be able to explain all the phenomena of nature.

And so it was not the atoms of matter but the atoms of electricity, the proton and the electron, that were believed then to be the sole particles of which the entire universe is

* Nine new elements have recently been added to this number. But none of them can exist in the stable state. The same is also true of another twelve elements of the above-mentioned ninety-two.

built and the properties of which were immutable and they themselves indivisible. It is true, physicists often encountered another, very special type of particle, photons, of which, according to present-day conceptions, all electromagnetic radiation consists. But no independent existence could be ascribed to these particles since they were always emitted solely by atoms or moving electrons and were very soon absorbed by others. Thus, they could be regarded as some sort of auxiliary particles which only convey energy from one atom to another and in this way put an end to their own existence, in contrast to the eternally existing and moving protons and electrons.

The 1930's brought big changes in the conceptions concerning the constitution of atoms of matter. The beginning was in 1932, when the American physicist Anderson used Skobeltsyn's method described above to measure directly the energies of cosmic particles passing through the entire atmosphere of the earth. A special cloud chamber designed for this purpose was placed between the pole pieces of a large and very powerful electromagnet, as shown in Fig. 20. Anderson sent a tremendous current of two thousand amperes through the windings of the electromagnet and obtained in the chamber an exceedingly strong magnetic field of 24 thousand oersted. This field was tens of thousands of times more powerful than that of the earth. A considerable portion of the charged cosmic particles that passed through the chamber was deflected. Just as in the later experiments of Vernov (in the stratosphere) it turned out that here, at sea level, too there were particles that possessed stupendous energies measured often in the thousands of millions of electron volts.

However, the biggest result achieved in Anderson's studies was the possibility of determining, in individual cases, the nature of the particles that leave tracks in the chamber.

Thousands of photographs were obtained and studied through the use of this new equipment. Anderson soon noticed a very interesting phenomenon: in a number of cases

the pictures showed two particles emerging from one point and then deflected by the magnetic field in different directions (Fig. 21). This meant that one of the particles of the

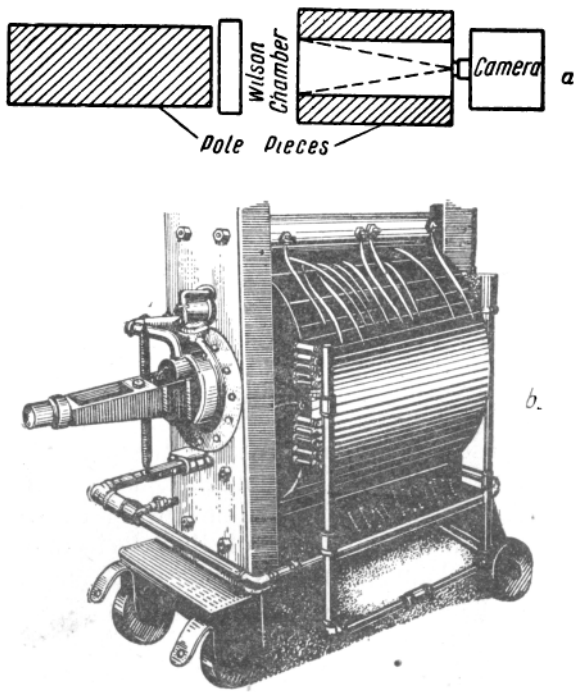


Fig. 20 *a*) General layout of Anderson's apparatus; *b*) general view

pair was charged positively and the other, negatively; in other words, one apparently was a proton and the other an electron (at that time no other particles were known). But the most interesting thing was that the tracks of both particles were usually very much alike. It was obviously impossible to think that one of the particles was nearly 2,000 times as heavy as the other, as it should be if we were dealing with a proton and an electron.

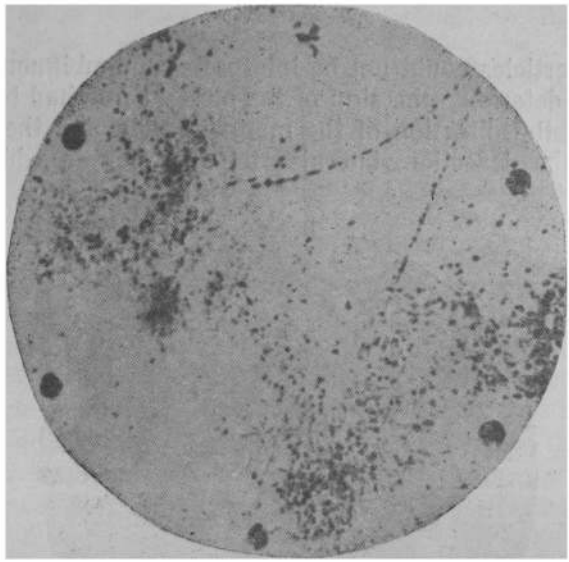


Fig. 21. One of the first photographs to show a pair of particles: one, charged negatively, is an electron; the other is positively charged but does not resemble a proton

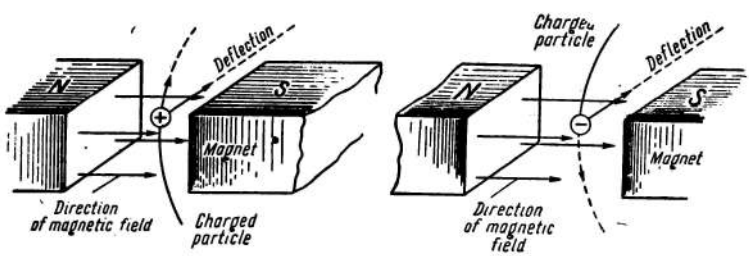


Fig. 22. In the above magnetic field, a positively charged particle moving up is deflected in the same direction as a negatively charged particle moving down and therefore they cannot be distinguished from each other

How could this be explained? Anderson decided to make a more detailed study of all the positively charged particles that he had seen on the photographs obtained. Single particles were in excess of pairs. However, the photographs of

single particles could not be interpreted unambiguously. In order to determine the sign of the particle, one had to know not only the direction of the magnetic field and the direction of the deflection, but also the direction in which the

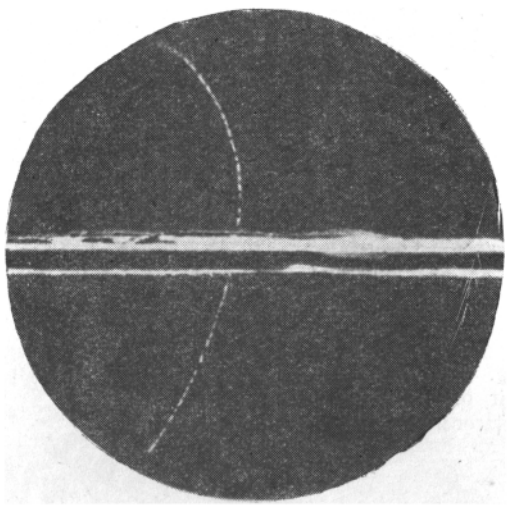


Fig. 23. The first photograph of a track belonging to a positron. This photograph made it possible to conclude that this particle differs from an electron only in the sign of its charge

particle moved along the track. As may be seen from Fig. 22, a positive particle moving up and a negative particle moving down are deflected in one and the same direction. True, the majority of the cosmic particles move down, but the possibility is not excluded that either the particle itself or another particle knocked out of the substance by it due to an encounter with an atom, may be reflected in any direction, including up.

But once a photograph was obtained of a single particle in special conditions. The photograph shown in Fig. 23 ex-

hibits the track of a particle which went through a 6-mm. plate of lead.

The interesting thing about this photograph is that it clearly shows that the path of the particle above the plate is curved by the magnetic field much more than below the plate, and this can occur only if the particle moved up and lost an appreciable part of its energy in passing through the plate. By determining in this way the direction in which the particle moved and by comparing it with the direction of its deflection in the magnetic field, it became evident that the track was left by a positively charged particle. After a thorough study of this photograph, Anderson and his associate Neddermeyer arrived at the conclusion that this track could in no way be attributed to the familiar proton: only a very low-energy proton could be deflected so strongly by a magnetic field, but the track of such a low-energy proton would be ten times shorter than the track in the photograph. It was clear that the track in the chamber belonged to a new, hitherto unknown positively charged particle, but one much lighter than a proton.

Anderson's discovery was soon brilliantly confirmed by other workers. In February 1933, Blackett and Occhialini published extensive data of similar observations made with the same apparatus as Anderson used, but of an improved type. Among the innovations was control of the cloud chamber by Geiger counters, which, as we have already pointed out, considerably boosts the percentage of "useful" photographs. With hundreds of photographs these workers amassed convincing proof that cosmic radiation really does contain new, hitherto unknown, particles of mass roughly that of the electron and with a charge equal in magnitude to that of the electron, only positive, not negative. The new particle was called a *positron*.

At a later date, Anderson and Neddermeyer also detected positrons of real terrestrial origin. It was found that certain substances irradiated by gamma rays of sufficient energy emit positrons. Observations of this phenomenon in

the gas that fills the cloud chamber showed that the birth of a positron is always accompanied by the birth of an ordinary electron that flies out of the same point, as may be seen in Fig. 21. Further detailed investigations of a number of workers, including those of the Soviet physicists Frank and Groshev, showed that all theoretical formulas fully agree as to the energies of the created positron and electron and their angles of divergence if the direction and energy of the incident photons are known.

In 1934, the eminent French scientists, Frédéric Joliot and Irène Curie discovered another phenomenon in which positrons were produced independently of any cosmic or gamma rays. Using alpha particles from a radioactive preparation of polonium to irradiate tiny targets of boron, magnesium or aluminium, these investigators detected a rather strong emission of positrons. Several minutes after irradiation ceased, positrons were still emerging from the target, but their number diminished to the same extent as the number of electrons emitted by naturally radioactive substances (radium, thorium, etc.) diminishes with time.

An explanation was soon found for this important phenomenon: under the action of high-energy particles, the atomic nuclei of boron, magnesium or aluminium are converted into nuclei of entirely different elements. However, these new nuclei are found to be unstable, decaying through the emission of their excess energy in the form of ejected positrons and sometimes electrons, thus again producing a change, but this time the result is stable atomic nuclei.

Such phenomena were termed artificial radioactivity and the processes involving the transformation of nuclei are usually referred to as nuclear reactions, by analogy with chemical reactions. It should be borne in mind that although the source of these positrons and electrons is atomic nuclei, the latter did not originally contain such particles; they are created in the very process of disintegration due to the excess of energy of not less than one million electron volts.

Thus physicists studying cosmic rays established for the first time a new fact that is of extraordinary and fundamental importance to the further development of cosmic ray theory and the structure of matter.

It was found that the elementary particles, these immutable (so it was thought) building "bricks" of matter,

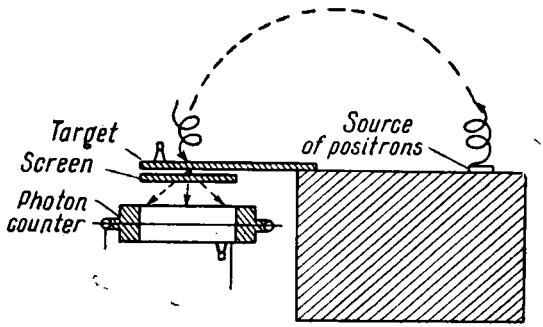


Fig. 24. Joliot's experiment. Positrons from a radioactive source are directed by a magnetic field to a lead plate; here they disappear being converted into photons. The photons are registered by a Geiger-Müller counter, which the positrons themselves do not reach as they are absorbed in the lead

which included such stable and "familiar" particles as the ordinary electron, can, under the proper conditions, be created anew and can disappear by conversion into new particles, photons, which are particles of radiation. The study of this phenomenon as well as of a series of other transformations involving elementary particles gradually brought scientists to a new level of knowledge at which the universal interrelationship and interchangeability of the basic forms of existence of matter stood out in bold relief, and in particular, the opposing of matter and radiation had lost its original meaning.

Up to now we have spoken of different cases when positrons were produced in one way or another. But what do

these positrons do next? To answer this question a simple thing would be to direct a beam of positrons from some artificially radioactive substance to the surface of a target and see what happens. That is exactly what Joliot subsequently did. It turned out that in such cases (see, for example, Fig. 24) the target began to emit rather high-energy photons. It was absolutely impossible to explain this energy by the loss of kinetic energy of the positron that was slowed up inside the target: the loss of energy by the positron was much less than the energy of the radiated photon. On the other hand, this energy may be explained by assuming that photons result from the incident positron combining with some electron of matter; in this case the positron and electron disappear entirely or, to be more precise, they are transformed into one or two photons. Theory predicts that such a process of transformation or, as it is generally spoken of, "annihilation"* of the positron occurs the sooner, the slower it is moving. Whereas a positron that has stopped altogether "dies" in such a tiny fraction of a second that it is impossible to measure it directly, the very fast positrons (and only they are detected in cosmic radiation) find time to participate in other phenomena and reveal themselves just as well as electrons. More details of this will be given presently.

We are now in a position to give a very definite answer to the question of how positrons appear and disappear in cosmic radiation. They are born in the earth's atmosphere by photons that are component parts of the cosmic rays (later on we shall speak about the origin of these photons). It should be pointed out that each time it is a pair (a positron and an electron) that is born. Both theory and experiment show that this process can take place only if a photon comes close enough to an atomic nucleus of air. In exactly

* The term "annihilation" is in this sense misleading since in actuality the particle does not vanish entirely. What takes place is the transformation of particles of matter into particles of radiation—photons.

the same way, electron-positron pair production can occur when these photons impinge on a solid substance, but this process is especially intense near the heavier nuclei that possess a large electric charge, and, consequently, a strong electric field, for example, in the vicinity of lead nuclei. The positrons then gradually slow down losing energy (this is partly due to ionization of the molecules of the surrounding matter), and, finally, usually at the very end of the "flight," they are annihilated, again producing photons, this time of very low energy. In their passage through matter, positrons, just as electrons, have still other "adventures" which we shall describe in the next section.

HOW DO CASCADE SHOWERS ARISE?

The attention of investigators studying cosmic rays at different altitudes was long ago arrested by the following fact. Cosmic ray intensity does not increase with altitude right to the top of the atmosphere; from a certain point it begins to diminish. It would seem that if cosmic radiation does not originate in the earth's atmosphere, but somewhere beyond, it can only be gradually absorbed in its downward movement, but it should in no way become more intense. But when counters were sent up in pilot balloons to altitudes of some 30 km. it was discovered beyond doubt that although the intensity of cosmic rays was greater than at the surface of the earth, it was several times less than at an altitude of 20 km. (Fig. 25*a*). Doesn't this signify that the rays are not cosmic in origin but arise in some way in the upper layers of the atmosphere, as some scientists had once thought?

The following rather simple experiment carried out in the Pamir Mountains by O. Vavilov can immediately convince you that this is not the case at all. If we register cosmic rays by using a thin-walled ionization chamber surrounded by a lead shield, and if we vary the thickness of this shield, we will obtain a familiar picture (Fig. 25*b*). As the thick-

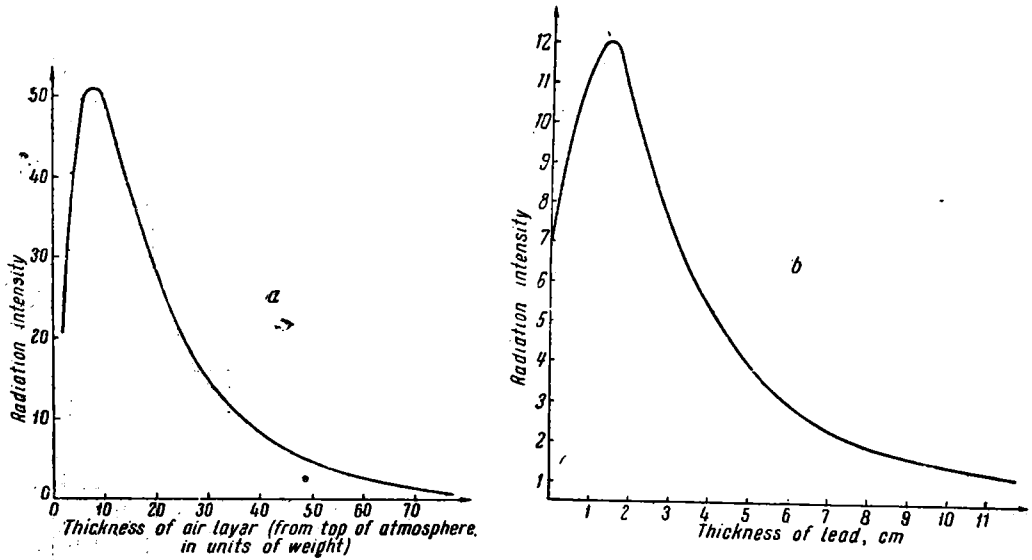


Fig. 25. Curve *a* depicts the initial growth and following reduction in the number of cosmic particles as they pass through the earth's atmosphere (the data of Pfotzer and Baradsey). The intensity variation obtained during the passage of particles through greater and greater thicknesses of lead is of the same nature (curve *b* was obtained by O. Vaviloy in measurements with an ionization chamber)

ness of the shield is increased, the intensity of the radiation at first increases perceptibly, and only when the thickness of the lead reaches about 1.5 cm. does it begin to fall off. Fig. 25 shows that the passage of cosmic rays through lead reminds us of their passage through the entire atmosphere of the earth; in both cases, the total number of charged particles in the first layers of the substance increases, and then diminishes more and more.

The explanation of this strange behaviour of cosmic rays was found in connection with the study of several very peculiar phenomena. Already the early cloud chamber photographs taken in 1928 by Skobeltsyn showed at times not individual tracks of particles but whole streams of them that seemed to erupt from the walls of the chamber (see Fig. 17, p. 40. On the average, one photograph in a hundred produced such streams, or as they are commonly called, showers, consisting of several particles. If we put a layer of lead over the chamber, the number and strength of the showers increase considerably, and it may be seen that the majority of them emerge from the lead. In some showers the number of particles reaches tens and even hundreds, so it is no easy task to analyse this complex picture.

To find out how a shower is formed and what it consists of, the following simple method is used. Lead plates, each several millimetres thick, are inserted in a cloud chamber. A photograph obtained in such a chamber is given in Fig. 26. It shows the usual birth and development of a shower. The upper plates of the chamber are penetrated by only one charged particle which knocks out of the lead several new particles; and each of these creates more new particles as it passes through successive plates. Such "multiplication" in several plates increases the number of particles very considerably. Sometimes it is seen that the shower originates at precisely the point where the upper plate is crossed by the track of a charged particle. But very often there is no "primary" particle above the lead plate, and the

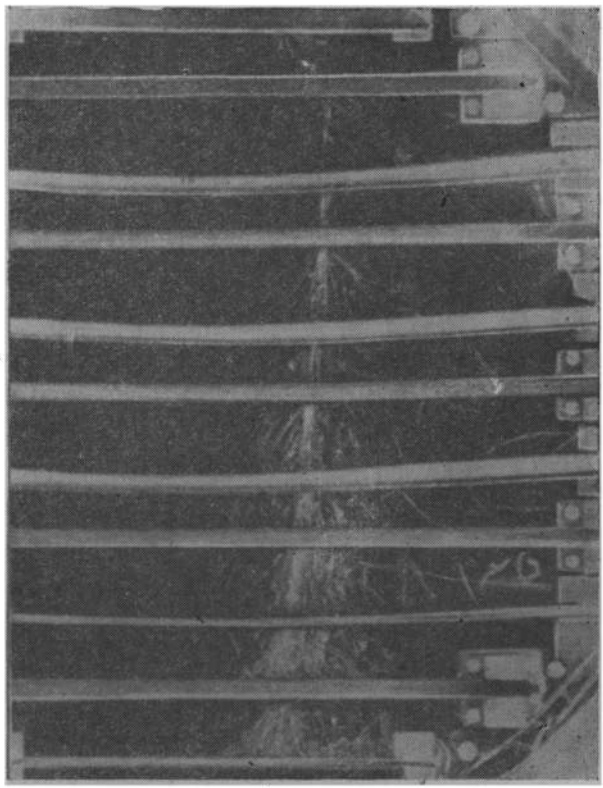


Fig. 26. A photograph showing shower formation in a cloud chamber with lead plates. The single ionizing particle (electron or positron) coming from above gradually "multiplies" in the processes of radiative collisions of photons and electron-positron pair production by the photon. In this process the energy of all particles gradually diminishes, as may be seen by the growing spread of shower particles

shower seems to originate from "nothing" (in actuality, however, an invisible photon in the chamber is the cause).

A simpler, but much less vivid method of registering showers that emerge from lead was used by the physicist

Rossi. He placed three counters in the form of a triangle (Fig. 27*a*) and without changing their position covered the whole set with layers of lead of varying thicknesses. Using a special electric arrangement Rossi recorded the number of simultaneous discharges in the three counters and obtained the following picture (Fig. 27*b*). As the layer of lead increases to 1.5 cm., the number of triple coincidences increases too, and then it begins to decrease with great-

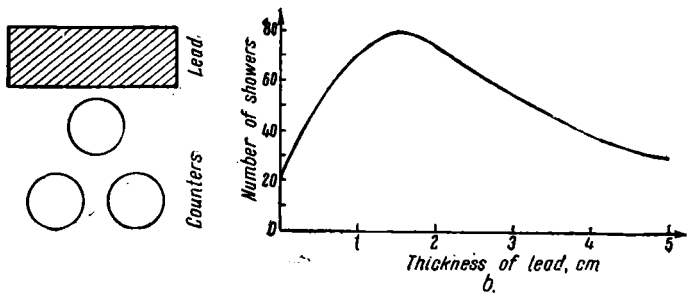


Fig. 27. Rossi's experiment showing showers created by cosmic rays in the lead above the counters. *a*) General arrangement of the apparatus; *b*) Variation in the number of registered showers with increasing thicknesses of lead

er thicknesses of lead. Comparing his experiment with what is observed in a cloud chamber with lead plates, Rossi also arrived at the conclusion that groups of particles or showers arise in lead and that as they pass through the lead they first increase in number and then are gradually absorbed.

Another phenomenon closely related to the preceding one was discovered in 1938 by the French physicist Auger. He studied cosmic rays with three Geiger-Müller counters (Fig. 28). Two of them comprised an ordinary telescope, and the third was placed at a distance that could be varied. As in the Rossi experiment, all three counters were connected in an electronic circuit, which was triggered only in the case of simultaneous discharges in all counters. One

can easily see that such a coincidence will occur when some ionizing particle passes through the telescope and simultaneously another charged particle passes through the supplementary counter. Of course, it may happen that different charged particles will pass through each counter, but still it is obvious that the probability of simultaneous passage of three different particles through the counters is

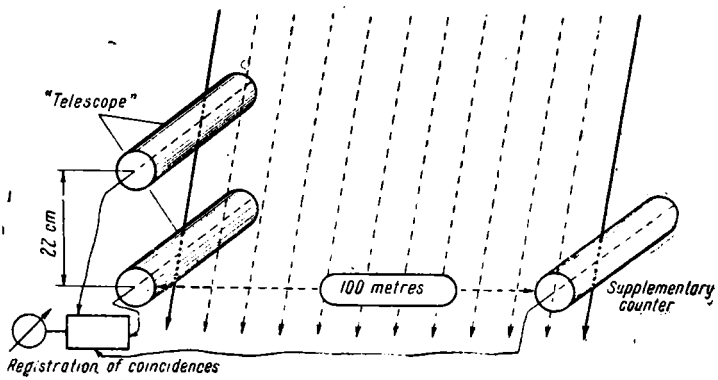


Fig. 28. The first experiment to show air showers up to 100 metres in width

considerably less. If all cosmic particles passed at random and were not connected in time, then even a simultaneous registration of two particles would, in Auger's experiments, be very rare, about once an hour, as estimates showed. For the case of such a fortuitous coincidence, the position of the side (third) counter is immaterial, the important thing being that one and the same particle should not pass through all three counters. Actually, however, these experiments showed that if the side counter was close by, such triple coincidences of discharges in all counters were hundreds of times more frequent than could be expected. As the third counter was moved away, the number of coincidences first diminished sharply and then more gradually, and only when the distance between the telescope and the supple-

mentary counter reached a hundred metres, only one coincidence was recorded per hour, which was to be expected in the case of a purely accidental passage of individual particles through the counters.

On the basis of his experiments, Auger concluded that cosmic particles did not always appear singly but sometimes in groups occupying at one and the same time a large area. Such broad groups of a large number of particles of cosmic radiation moving simultaneously in the air were called extensive air showers or Auger showers.

Skobeltsyn later pointed out that by improving the apparatus the number of accidental coincidences recorded could be reduced and measurements could be extended to distances up to one kilometre. It was found that even at such great distances the number of cases of simultaneous passage of several particles in the air is still in marked excess of the number of accidental coincidences.

All the phenomena that we have just been discussing are, it appears, closely related and can easily be explained by electron-positron pair production from high-energy photons. As we have already mentioned, photons of cosmic radiation can be transformed into pairs of electrons and positrons during collisions with atomic nuclei of the air, but this process proceeds much more easily in substances with heavy atomic nuclei, such as lead.

Now what happens to the newly born electron and positron which continue to move in approximately the same direction as the primary photon after having divided up the latter's energy? Obviously, such fast particles will lose their energy in ionization of the atoms of the substance. However, their fate depends not so much on ionization as on another process. It has long since been known that when fast electrons impinge on a solid substance they are slowed down very strongly and emit a definite electromagnetic radiation. This is the same phenomenon that is used in an X-ray tube to obtain X-rays by "bombarding" a refractory target with a stream of electrons having energies

of tens of thousands of electron volts (Fig. 29). Such radiation by collision is called bremsstrahlung, and is due to the fact that an electron is a charged particle, and a very light one. These two peculiarities of the electron are enough for it to be slowed down sharply when encountering atomic nuclei (this is because of electric forces that arise when an electron comes close to a charged nucleus). The slowing down is especially pronounced in heavy substances that have nuclei with big electric charges as, for example, in

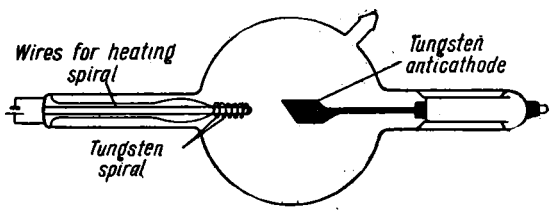


Fig. 29. An X-ray tube in which X-rays are produced by the sudden deceleration of fast electrons in a metal plate (the anticathode). The source of these electrons is a tungsten spiral heated by a current

lead. Obviously, the above should apply equally to the positron, which differs from the electron only in the sign of its charge. In this case also, impacts with atomic nuclei lead to sharp deceleration due to electric forces and consequently to strong bremsstrahlung. The heavy proton, on the contrary, will not be decelerated sharply by these same nuclei, and therefore, there should be practically no radiation.

The theory of this phenomenon shows that the energy lost in radiation increases rapidly with the energy of the light particle so that in the case of the electrons and positrons of cosmic radiation with their enormous energies, such losses are, as a rule, many times greater than the energy losses due to ionization of matter. These energy losses are especially great in lead so that the average "cosmic" electron actually gives up nearly all its energy in a layer of lead of

only several centimetres, whereas in the same layer of light aluminium, for instance, only a small part of the energy is lost in radiation.

Thus, we should expect that in any substance, and especially in such a heavy one as lead, the movement of an electron or positron of high enough energy will be accompanied by constant emission of bremsstrahlung photons followed by the reverse transformation of each photon into an electron-positron pair. Whereas in air an average of 300 m. of path is required for each transformation, in lead five millimetres is enough. If any one of the three particles possessing very high energy enters the earth's atmosphere, it will have enough time as it passes downward to "multiply" hundreds, thousands, and millions of times before reaching the surface of the earth. The particles thus generated will gradually diverge from the original direction and scatter,* covering a larger and larger area in the form of a denser and denser shower of simultaneously moving charged particles and photons. It is precisely this process that gives rise to an extensive air shower (Fig. 30).

Inasmuch as the whole development of the shower may proceed at the expense of the energy of a single original "progenitor," the energy of each particle in the shower is reduced on the average as many times as the number of particles is increased, because the total energy remains nearly constant. If we take account of the energy losses due to ionization, the reduction of energy of the particles comprising the shower will be still more pronounced. As soon as the average energy of the particles of the shower falls below a certain critical value (equal approximately to 80,000,000 electron volts for air), the processes of pair production and bremsstrahlung cease to play a marked role, and then the number of particles in the shower falls off rapidly because of their absorption, which is due to degradation of energy through ordinary ionization of the atoms of the substance.

* As may be seen from Fig. 26, this scattering increases as the particles of the shower lose their energy.

In this ionization, though the total number of charged particles comprising the shower continues to increase, the new electrons (there will now be no new positrons) knocked out of the atoms by ionization have such small energies

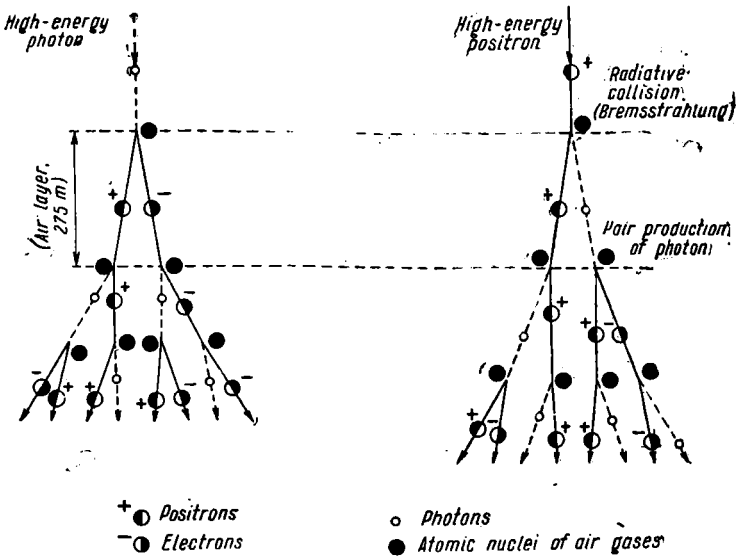


Fig. 30. The birth and development of a shower from a single photon and one positron during their passage through the air; a similar process in the lead plates of a cloud chamber is shown in the photograph in Fig. 26 (photons are of course not visible there)

that they do not usually "multiply" any more and are absorbed in relatively thin layers of matter. At any rate, a slight increase in the number of particles at low energies due to ionization is very soon compensated for both by stopping of the particles which have completely frittered away their energy and by strong scattering of the slow moving particles in all directions, including backwards.

Does this mean that at low altitudes cosmic rays can no longer produce new showers? Of course not. First of all,

different particles in one and the same shower developing in the air lose their energy in different degrees, so that even at low altitudes some of them still have enough energy to form new showers. The principal thing, however, as we shall see later, is that there are other processes which produce high-energy photons in the very depths of the atmosphere. This is the reason why everything observed in Rossi's experiment (Fig. 27), and especially in the cloud chamber with lead plates, is easily explained from the viewpoint of successive, or, as it is called, cascade "multiplication" of particles and their subsequent absorption.

Studies of the nature and properties of cascade showers constitute a very important chapter of cosmic ray research. The theory of the formation and development of these showers (the so-called cascade theory), begun in 1937 in the works of outstanding foreign and Soviet theoreticians, was later worked out in detail by many scientists, especially the Soviet theoretician Belenky. The cascade theory was able to describe the passage of a portion of cosmic radiation, consisting of photons, electrons, and positrons, through the earth's atmosphere. Using this theory, one may calculate, as Skobeltsyn, Migdal and Pomeranchuk did in their time, the number and energy of the particles and other properties of extensive showers in the air. Later experiments showed that all these computations produced a generally correct picture of events.

It was noted, for instance, that the Auger showers in which tens of particles arrive on each square metre of the earth's surface, covering at a single time areas up to several hectares (1 hectare=2.47 acres), arise from very rare particles that possess stupendous energies. This energy is no less than millions of times the mean energy of all the remaining particles of cosmic radiation and attains at times fantastic magnitudes of millions of millions of millions of electron volts (10^{18} ev) and the total number of particles in big air showers runs into the millions. That is the reason why such showers are counted by the dozen an

hour using Geiger-Müller counters covering a total area of only several hundred square centimetres. If these high-energy primary particles came to the earth without producing powerful showers in the air, one would have to wait centuries with these counters to register even a single such particle. Thanks to air showers, we not only know that such particles exist, we can even compute their energy.

THE ELECTRONS THAT FAILED

What we have related concerning the development and "dying out" of showers would seem to permit an explanation of the general course of cosmic radiation intensity with altitude: as electrons, positrons and photons pass through the earth's atmosphere their number increases rapidly at first due to the development of showers; then, from an altitude of about 20 km., it diminishes more and more due to absorption of the shower particles.

This was the conclusion arrived at by many workers during 1938-39. They assumed that all the primary cosmic rays were light charged particles, electrons and positrons.

In 1941, the American physicist Shain made an attempt to prove the correctness of this viewpoint by the following experiment, which was very simple in principle but not very successful in execution. It resembled somewhat Rossi's experiment. He used pilot balloons to send up 27 kilometres a system of counters that recorded showers (produced in a piece of lead) of a large number of particles. If the primary cosmic rays consisted entirely of electrons (and also positrons), then there should arise in the lead frequent and powerful cascade showers due to the huge energies of these particles. To the general surprise, Shain's apparatus hardly registered such showers at all.

To explain this unexpected result, Shain put forth the assumption that the primary radiation does not consist of light electrons or positrons, but of heavy particles, protons. In support of this assumption, he pointed to the results of

his other experiments which showed that even in the topmost layers of the stratosphere an appreciable number of charged particles can pass through thick layers of lead. These particles could not be electrons.

Shain's conclusion was, of course, nothing more than a new, as yet unproven, assumption, a hypothesis that required careful verification. New and refined experiments at high altitudes were necessary.

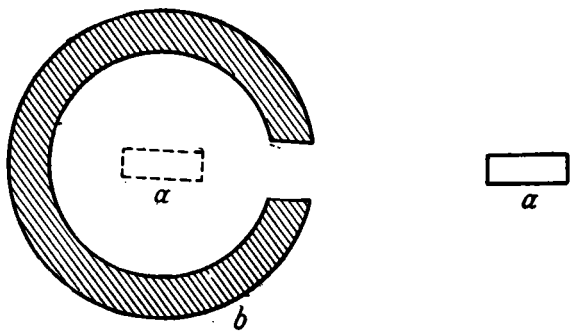


Fig. 31. *a)* A small ionization chamber or counter; *b)* A lead sphere

Such experiments were carried out during several post-war years by a group of Soviet physicists under the supervision of Vernov, who designed a large number of original automatic instruments to be sent up on substratostats or sounding balloons. The apparatus carried by the sounding balloons reached altitudes of fully 30 km. and was supplied with a newly designed and reliable telemeter system for the simultaneous transmission of various data. This, in its turn, greatly extended the possibilities of research at high altitudes as compared with Shain's experiments.

First of all, Vernov suggested a new method for counting the number of electrons and measuring their mean energy. This method far outstripped the one Shain used both in reliability and precision. Whereas Shain endeavoured to register individual showers that were created in

his apparatus by electrons of sufficiently high energy, Vernov utilized this same property of electron multiplication in lead in an entirely different way. A small ionization chamber or counter (Fig. 31) was used to register all

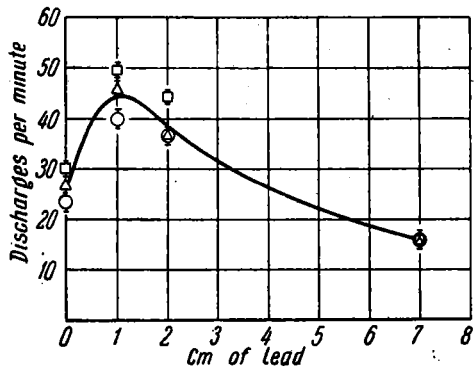


Fig. 32. A transition-effect curve in lead obtained by Vernov and coworkers in stratosphere investigations. The character of the increase and then the decrease in the number of particles with varying thicknesses of lead that surrounds the counter is convincing proof that the principal part of the observed radiation is made up of electrons of relatively low energy (of the order of a hundred million electron-volts)

charged particles existing at a given altitude in the stratosphere. The instrument was then surrounded by a lead shield of variable thickness; an increase of radiation intensity was noted to depend on the thickness of the lead shield. Fig. 32. shows the characteristic curve obtained at high altitudes. It expresses the number of particles registered in the given experiment as a function of the thickness of the lead and is commonly called a transition effect curve.

It may be seen here that as the counter is progressively surrounded by more lead, the number of registered particles first increases, due to multiplication of electrons, by a factor of approximately two (in the case of a one-centimetre thickness of lead) and then falls off. This type of curve may easily be explained on the basis of the cascade theory if we

assume that all or the bulk of the observed particles are electrons of relatively low energy, of the order of a hundred million electron volts. At the same time, if the electrons were primary particles of cosmic radiation, then the transition effect in lead would appear differently. First of all, the "multiplication" of electrons at high altitude would be much stronger because of their enormous energies which are necessary in order to overcome the earth's magnetic field. And only at lower altitudes where electron energy has already fallen off sharply could there be only a two-stage "multiplication" as was actually observed for all altitudes. It became obvious that the observed electrons were not primary but secondary particles and were created by primary particles of a different nature and already at altitudes of 25 km. above sea level and lower.

Another series of experiments of Vernov and coworkers was devoted to an elucidation of the nature of the primary radiation itself using as a basis the geomagnetic effect, that is, the influence of the earth's magnetic field on this radiation.

Experiments dealing with the geomagnetic effect were usually planned so as to study the reduction in intensity of the radiation observed in the stratosphere as one moves from higher altitudes towards the equator (the so-called latitude effect). As has already been pointed out, these were precisely the experiments that led to the conclusion that the major portion of the primary radiation consists of charged particles with energies of several thousand million electron volts. In order to find out whether these particles are really protons, as Shain thought, the sign of their charge had to be determined. To do this one might make use of the earlier experiments of the American physicist Johnson dealing with the so-called effect of azimuthal asymmetry of cosmic rays.

Calculations show that the effect of the earth's magnetic field on positive and negative particles is different. If only particles moving from east to west are registered (by a tele-

scope of counters), it will be noted that the magnetic field has sifted out mostly particles with a positive charge and only a small portion of negative particles of relatively low energy. On the contrary, when observing particles moving from the west, it is found that only a small portion of high-energy negative particles enter the telescope. In this case, the effect on them of the earth's magnetism is much greater than that on the positive particles. However, during his observations in the stratosphere, Johnson did not detect any marked difference in the readings of a telescope facing the west or the east. Apparently, this was due simply to his imperfect apparatus which was unable to hold the given direction accurately.

Many attempts were made at later dates to improve on Johnson's experiment. The most convincing results were obtained by Vernov and his collaborators in 1949; their original type of automatic apparatus used photocells to keep the telescope directed precisely east and west in alternation; bearings were taken by the sun. Five flights with this apparatus were sufficient to establish conclusively that the number of particles coming into the instrument from the west was approximately twice as great as the number coming from the east. If the energies of primary particles determined from the latitude effect are taken into account, it may be stated that only positive particles of very high energies come from the east. In this case, the magnetic field of the earth does not affect them.

On the basis of all the experiments described here it was proved with finality that the primary particles of cosmic radiation are principally positively charged particles that are much heavier than electrons. After this, it was hardly possible to doubt that these particles were protons.

A new method of investigating primary cosmic radiation has been developed in recent years. The apparatus is sent up not on sounding balloons but in V-2 type rockets. The results obtained afford direct confirmation of the present viewpoint that the primary radiation outside the earth's

atmosphere consists basically of protons. However, despite their technical complexity and the large amounts of money spent, these experiments have not as yet added anything essentially new to our knowledge of cosmic rays. The reason is, firstly, that measurements on rockets last only a short time, several minutes at the most, and, secondly, the measuring apparatus is surrounded by the massive body of the rocket, and because of processes that take place within this body, radiation from above cannot be observed in the pure state.

Lately Soviet scientists have carried out a number of investigations under the programme of the International Geophysical Year by means of two artifical satellites of the Earth. They have obtained some data on the intensity of solar radiation in the short-wave, ultraviolet and X-ray regions of the spectrum, as well as valuable information on cosmic rays.

Chapter V

MESONS IN COSMIC RAYS AND IN THE ATOMIC NUCLEUS

WHERE DO COSMIC RAYS GET THEIR GREAT PENETRATING POWER?

We have already seen that cosmic rays differ from all other invisible rays primarily in their tremendous penetrating power. Indeed, numerous measurements have shown that these rays are capable of piercing a layer of lead more than one metre thick and may be detected many hundreds of metres below the surface of the earth. If cosmic rays consisted entirely of photons, electrons and positrons such penetrating power would be out of the question, despite the huge energies of these particles.

From the previous chapter it is clear that in passing through matter all these particles generate showers intensively, especially in such heavy materials as lead. Enormous energy is spent on the formation of showers, and it increases with the energy of the primary particles. Experiments using cloud chambers with plates have shown that all showers obtained even from rather energetic rays are, as a rule, absorbed *in toto* in only a few centimetres of lead. And the conclusion arrived at by the cascade theory is that as the energy of the primary particle increases even so much as many thousands of times, the mean penetrating power of a shower generated in lead increases only about 4 to 5 cm. (Fig. 33); for this reason, the penetration even

of an inappreciable fraction of particles of a cascade shower through a metre thickness of lead is out of the question.

This means that particles possessing a large penetrating power (and at sea level they make up about $^3/_4$ of the total number of charged particles) can be neither electrons nor

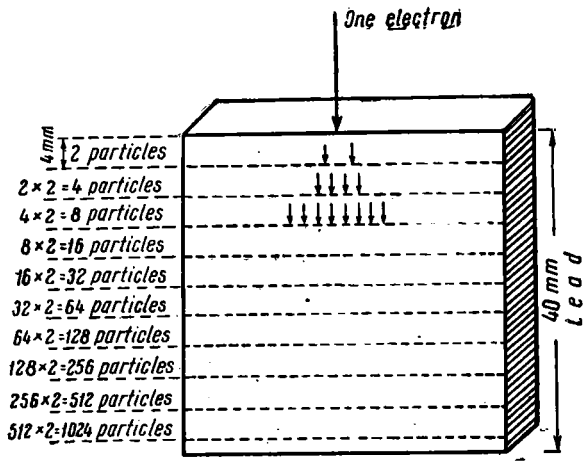


Fig. 33. What is the "secret" of the strong absorption of particles that create showers? If we consider that in every 4 mm. of lead each such particle is converted, on the average, into one pair of particles of half the initial energy, the energy of the particles in traversing 4 cm. of lead will have diminished 1,000 times, in 10 cm., one million times and in 15 cm. a thousand million times!

positrons nor photons. Electrons and positrons are readily absorbed in lead because in passing through it they lose much more energy than is required solely for the ionization of its molecules; this additional energy loss is due to shower formation and increases with the energy of the particles. If some sort of penetrating particles do exist, they must lose considerably less energy in traversing lead; this amount should only equal that required for ionization of the lead atoms if these particles are charged.

As far back as 1937, Anderson and Neddermeyer began an experimental check of the above ideas. Using a cloud chamber they succeeded in proving that there exist pene-

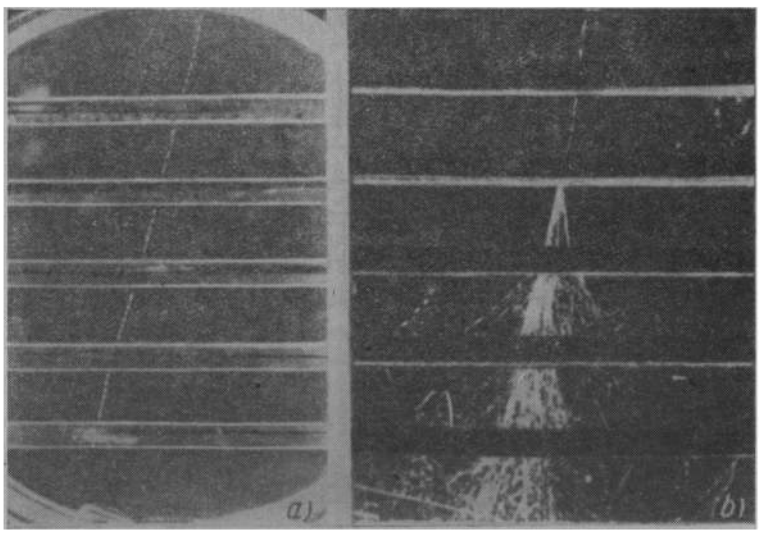


Fig. 34. Photographs in a cloud chamber with lead plates. It may be seen from these photographs that some particles are not capable of creating showers (*a*), while others, on the contrary, produce them very intensively (*b*). It is precisely for this reason that the first type of particles is often able to pass through a metre of lead, whereas the second type of particles is unable to penetrate more than several centimetres (provided the initial energy is the same)

trating particles which actually do not produce showers at all and which lose a minimum of energy, that is, only through ionization of the surrounding matter and in no way by the emission of photons (Fig. 34). How are we to explain this peculiarity of the penetrating particles? The explanation is simple if we recall how "multiplication" of particles in a shower takes place. First a primary particle passing near an atomic nucleus is decelerated and emits

a photon, which then collides with another atomic nucleus and gives birth to an electron-positron pair. If the primary particle is considerably heavier than an electron, its deceleration will be less and no photon will be emitted, which means that there will be no shower. For this reason, it was to be expected that the penetrating particles are charged particles with a mass much greater than that of an electron.

A PARTICLE TOO HEAVY TO BE AN ELECTRON AND TOO LIGHT TO BE A PROTON

Continuing their work with a cloud chamber placed in a strong magnetic field, Anderson and Neddermeyer collected a very large number of photographs with tracks of charged particles of cosmic radiation. In the study of each track they paid attention, first, to the thickness or, more precisely, to the density of the track, and secondly, to the degree of curvature produced by the magnetic field.

As was already established from Skobeltsyn's first experiments, the majority of the tracks are very similar to the familiar tracks of fast electrons. But the density of a track is determined by the capacity of the particles to ionize gas molecules, and this capacity is the greater, the bigger the charge of the particle and the smaller its velocity. On the other hand, the velocities of the majority of the cosmic particles are close to that of light and are, in this respect, hardly distinguishable from each other. This means that the charge of the majority of particles, including the penetrating ones, cannot be very noticeably different from the magnitude of the charge of an electron or proton (the ionizing capacity does not depend on the sign of the charge).

In order to understand fully the nature of these penetrating particles, a measurement of their masses was necessary. This was done independently and almost simultaneously by Street and Stevenson, and by Anderson.

The success of these workers was due to the fact that they were able to catch the penetrating particle at the end of its flight, that is, when its speed was already very much less than that of light and the whole track came to an end inside the cloud chamber. Although there are as yet only a few such photographs (one is shown in Fig. 35), any one of them provides irrefutable proof of the existence of a new particle, as we shall now see. If the cloud chamber has been used in conjunction with a magnetic field, a track of this type enables three values characterizing the given particles to be determined straightaway. First, as was pointed out earlier, the momentum of the particle (it equals the mass times the velocity) may be found from the radius of the arc described by the particle under the action of the magnetic field. Second, a rough estimate of the speed of the particle may be made from the density of the track. And, finally, from the length of the track we may find the total number of ions produced by the particle, and hence also the entire energy the particle spent over this distance in the formation

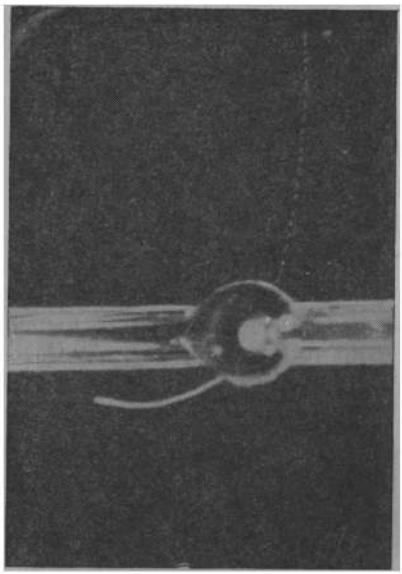


Fig. 35. A photograph giving evidence of the existence of a new particle, the mesotron (meson). The density, length and the curvature of the track across the counter, which is inside a cloud chamber, enables one to evaluate the mass of the meson: it is 180 to 200 times as heavy as the electron, or 9 to 10 times lighter than the proton. (This photograph was made by Anderson.)

of ions. If we know any two of these three values it is relatively easy to evaluate what interests us, the mass of the particle.

A thorough examination of the photograph showed that the newly discovered particle had a mass approximately 200 times that of the electron, or one-ninth that of the proton. At first this particle was called a heavy electron, then a mesotron and finally a meson, which means "a particle of intermediate mass." Recent and more accurate measurements of the mass of an ordinary meson give approximately 210 electronic masses.

Since the mass of a meson is great in comparison to that of an electron, it does not as a rule produce bremsstrahlung even in the heaviest substances (this is precisely what makes it easy to distinguish a meson from an electron in a cloud chamber with plates of lead, for the meson does not ordinarily produce showers). Thus, the meson loses very little energy in matter, and consequently it has extraordinary penetrating power.

Incidentally, the slight energy losses are to be explained not only by the big mass of the meson; we shall see later that there are still heavier particles (for example, protons) which do lose considerable energy in the production of showers. However, these showers are not associated with the emission of photons.

THE "SECRET" OF THE STABILITY OF THE ATOMIC NUCLEUS, THE PROBLEM OF BETA RAYS AND MESON DECAY

The discovery of the new meson particle played a big role in cosmic ray studies because it immediately made it possible to explain many puzzling properties of these rays (for instance, their extreme penetrating power). But the significance of this discovery is not confined solely to cosmic

ray studies; it also attracted the attention of nuclear physicists. This was the field in which the discovery of the meson served as one more proof of the power not only of experimental but also theoretical physics.

It turned out that already three years before Anderson's discovery, theoreticians had predicted not only the existence of a particle resembling the meson, but had described such of its properties as no one at first had even suspected. This prediction has its own instructive history.

As far back as 1913-14 the English physicist Rutherford, on the basis of his experiments in the scattering of alpha particles in thin layers of material, established the fact that the atom represents something in the nature of a miniature solar system with negative electrons revolving about a positively charged nucleus in the centre. For a long time it was believed that the nucleus itself consisted of both protons and electrons. However, quantitative theory which endeavoured to explain such nuclear structure came up against absolutely insurmountable contradictions. Besides, in 1932 a hitherto unknown neutral particle was discovered through the experiments of Bothe and Becker. After a detailed study of the properties of the new particle, called a neutron, it was found that it possessed a mass close to the mass of the proton, and already in 1933 the Soviet theoretician D. Ivanenko expressed the opinion that neutrons play a fundamental role in the structure of matter, forming, together with protons, the atomic nucleus. This hypothesis was soon brilliantly confirmed and there is no longer the slightest doubt that the atomic nuclei of the different chemical elements differ precisely in the number of component neutrons and protons (Fig. 36).

Nevertheless, from the very beginning great difficulties were encountered in the attempt to substantiate Ivanenko's hypothesis. These difficulties could be overcome only by applying fundamentally new ideas and concepts concerning the properties of the basic nuclear particles, the neutron

and the proton. First of all, it was totally impossible to explain the stable existence of a tiny positively charged central nucleus by ordinary electromagnetic interaction between its component parts. A large number of facts and theoretical ideas showed that there could be neither electrons nor positrons in the nucleus. But if such was the case, how was one to explain the fact that the protons in the

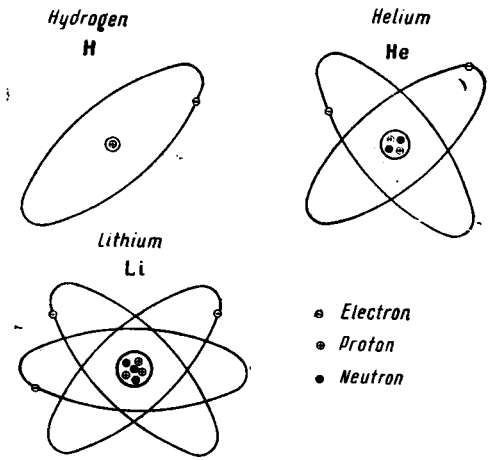


Fig. 36. A modern model of the atom. The structure of the atomic nucleus is determined by the number of protons and neutrons that go to make it up, and the number of electrons revolving about the nucleus and the character of their movement are determined by the number of protons. The figure shows the structures of the three simplest atoms, hydrogen, helium, and lithium

nucleus did not fly apart in all directions despite the tremendous electrical repulsion that arises when electric charges of one and the same sign come into close contact? How was one to explain that in the decay (whether natural or radioactive) of a large number of nuclei we still see either

an electron or a positron ejected? And what holds neutrons inside the nucleus, since they haven't any electric charge in general, and are therefore not affected either by attraction or repulsion of other particles?

All these phenomena could be explained only by assuming that the protons and neutrons in the nucleus are mutually attracted by some still unknown forces that are not at all electromagnetic in origin. When the particles are in close contact with one another these forces must be many times greater than ordinary electrical forces that produce the mutual repulsion of like charged particles, such as protons. What is the nature of these forces called nuclear forces, and how do they act?

In 1934, the Soviet theoreticians Tamm and Ivanenko independently of each other expressed an opinion that served as a guide in the explanation of nuclear forces. They proceeded from the fact that the interaction of two electric charges, including those of protons, may be represented as a constant exchange of quanta of an electromagnetic field, or photons, through whose agency energy is transferred from one charge to another. If it is assumed that protons (and also neutrons) can emit and absorb some other particles besides photons, then the exchange of such particles must inevitably lead to some sort of additional energy exchange, and consequently to an additional interaction. This additional interaction is not directly associated with the presence of an electric charge and may equally be manifested between two protons as between two neutrons or between a neutron and a proton.

Using a similar idea, the Japanese theoretician Yukawa advanced a theory in 1935, which, although far from perfection, gave a qualitatively correct explanation of the principal peculiarities of nuclear forces. He proceeded by generalizing the laws of action of ordinary electromagnetic forces. It was enough to know that in contrast to electromagnetic forces, nuclear forces should sharply diminish beyond the limits of the atomic nucleus, that is, at distances

of several millionths of a millimicron (a millimicron is a millionth of a millimetre). It turned out that in this case the transferred particles, unlike photons, must possess a considerable rest mass, and therefore Yukawa called these new particles heavy photons. Knowing the size of the nucleus, and thus also the distances over which the exchange of heavy photons could take place between protons and

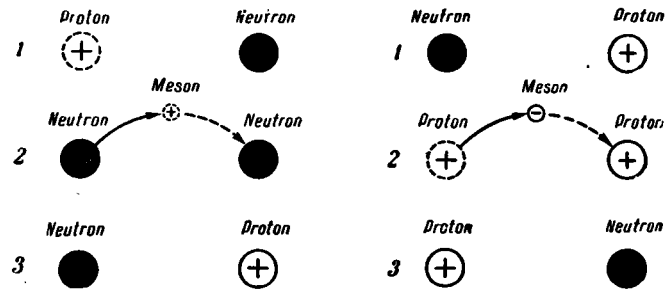


Fig. 37. The interaction of a neutron and a proton in the atomic nucleus according to the Yukawa theory: energy is exchanged through the agency of positive and negative mesons

neutrons, Yukawa was able to compute the mass of the heavy photon: it should be approximately 200 electronic masses, which agrees with the above-stated value of meson mass.

Besides mass, some of the heavy photons, or mesons, can also have an electric charge (positive or negative), equal in size to a proton charge. Using this charge, Yukawa attempted to explain not only the existence of stable nuclei, but also the absolutely unintelligible phenomenon called beta decay, that is, the transformation of one nucleus into another with the emission of an electron or positron. The explanation was this. Any positively charged proton of the nucleus (Fig. 37) can emit a positive meson, and, in accordance with the law of the conservation of charge, the proton itself is converted in the process into a neutron. In its

turn, another neutron in the nucleus absorbs this meson and is converted into a positively charged proton. As a result the total number of protons and neutrons in the nucleus does not change. In the very same way, energy is exchanged through the agency of the negative meson; first a neutron emits a negative meson and converts into a proton; another proton instantly absorbs this meson, and turns into a neutron with greater energy.

Through the constant exchange of energy by means of mesons, the nuclear particles (protons and neutrons) are bound into a single compact unit, the atomic nucleus. The structure of the nucleus resembles that of a liquid drop made up of a certain number of interlocked molecules.

Let us now assume that the meson can decay "en route" from the proton to the neutron or vice versa, so that, for example, a negative meson is converted into an ordinary electron that takes with it all the energy of the heavy photon. Such an electron will fly out of the nucleus at a very high speed, and due to the loss of a negative meson in the nucleus one of the neutrons will turn into a proton without any reverse transformation of another proton into a neutron. In the same way, a positron may be emitted from the nucleus: one of the protons of the nucleus, having become a neutron, will emit a positive meson, which will not have time to be absorbed by another neutron and will turn into a fast positron and fly out of the nucleus (see the example in Fig. 38). The explanation suggested by Yukawa is confirmed by the fact that when a positron is ejected by the nucleus the positive charge of the nucleus is always reduced one unit, but the total mass remains practically constant; this means that the emission of a positron by the nucleus is always accompanied by the conversion of one of the nuclear protons into a neutron. It was also known that the emission of an electron by the nucleus is always accompanied by the reverse transformation of one nuclear neu-

tron into a proton. But it is necessary at this point to note one more very important fact. All the basic laws of physics, including that of the conservation of energy, will be obeyed during meson decay only if we assume that simultaneously with the electron or positron there is ejected another, light, but uncharged particle, the so-called neutrino. Due to its

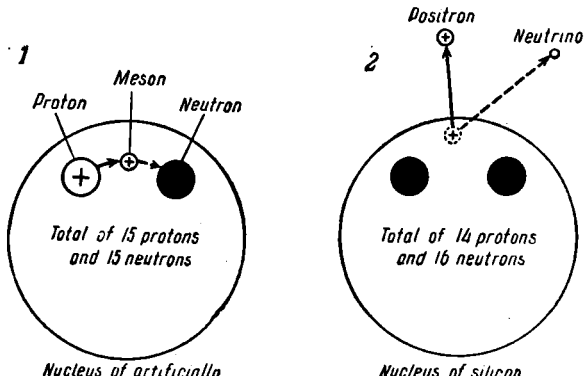


Fig. 38. How do we explain the decay of an unstable nucleus of phosphorus with the emission of fast positrons? A heavy photon converts into a positron which emerges from the nucleus together with a hypothetical neutrino. This reduces the number of protons in the nucleus by one and increases the number of neutrons also by one

small mass and lack of charge, this particle has as yet not been registered by anyone directly. Nevertheless, different physicists have done a number of experiments that enable the neutrino to be detected indirectly.

As soon as mesons were discovered in the cosmic radiation, Yukawa, and others also, asked the very natural question: is not the meson of cosmic radiation precisely the heavy photon by which proton-neutron interaction within atomic nuclei is accomplished? Indeed, the size of the charge and the mass of the meson were just the same as Yuka-

wa's heavy photon. In addition, it was found that roughly one half of the "cosmic" mesons carry a positive charge and one half negative, which again was easily explained from Yukawa's viewpoint.

Soon experimental results were published that seemed not to leave a shadow of a doubt that the penetrating particles of cosmic radiation consist entirely of mesons knocked out of the atomic nuclei of atmospheric air.

It is hard to overestimate the tremendous role that was played and that still will be played in science by the discovery of the meson. If we look to history for analogies we may compare it with the discovery of radio waves. Prior to the latter discovery, electric and magnetic forces and fields of force in physics were regarded as auxiliary concepts. Radio waves became a real and highly effective embodiment of these fields that can exist independently, apart from matter. In the same way, with the discovery of mesons physicists for the first time became acquainted with waves, or, more precisely, field quanta of nuclear forces and obtained the real possibility of investigating this field in the free state, a state "isolated," so to speak, from the atomic nucleus.

During the years 1939-41 numerous workers established the fact that absorption of mesons in air is much more intense than might have been expected on the basis of absorption in solid matter. The point is that due to their large mass, mesons are almost altogether unable to emit collision radiation and in traversing matter they lose energy only by ionization of atoms. But the total number of electrons in the electron shells of different atoms is roughly proportional to the weight of their nuclei, for the number of electrons around the nucleus is always equal to the number of protons in the nucleus (otherwise the atom as a whole would not be neutral) and the total number of particles in the nucleus (protons and neutrons) is numerically equal to the atomic weight and is always about twice the number of protons. All this implies that equal-weight layers of dif-

ferent substances should absorb mesons in about the same degree.

In order to verify the accuracy of this rule, the following experiment was repeated several times. A telescope of several counters was used to measure the number of mesons passing through a given apparatus during a definite time.

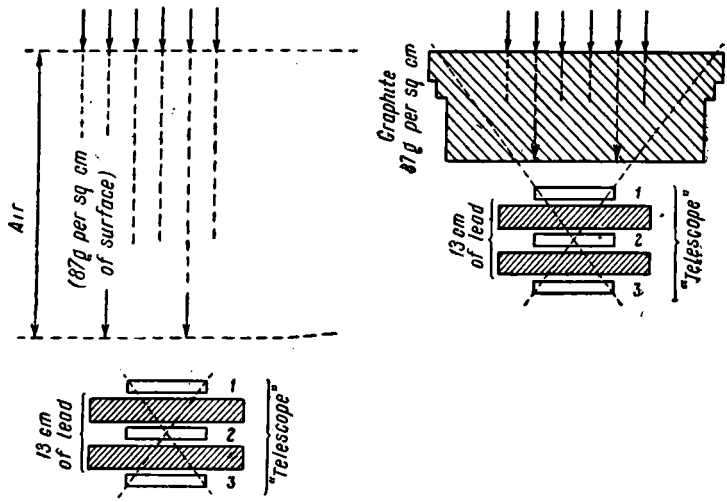


Fig. 39. An experiment that proves the anomalously large absorption of mesons in air: the absorption of mesons in a layer of solid substance (graphite) of the same weight as air is much less

Lead placed between the counters of the telescope (Fig. 39) absorbed completely all entrant electrons. The experiments were conducted at two different altitudes above sea level. At the upper altitude an additional layer of some substance, such as graphite or aluminium, was provided. The total weight of this substance (calculated per square centimetre of surface) equalled that of the column of air between the two altitudes. Since the mesons coming from above would in both cases have to pass through the same quantity of matter (in weight), the results of the meas-

urements, it would seem, should not differ. Actually, however, at the lower altitude the number of mesons detected was always noticeably less, and this meant that

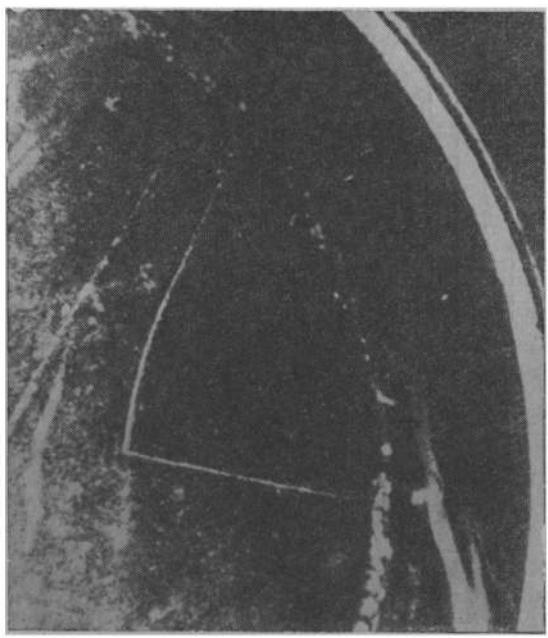


Fig. 40. A photograph that reveals the decay of a meson slowed down in a cloud chamber; the thinner track belongs to a light but fast particle, which can only be an electron

air absorbs them much more intensively than any solid substance.

There was only one possible explanation of this strange fact, and it was the one that conformed to Yukawa's views. Mesons spend much more time in passing through such rarefied matter as air than in passing through an equal (by weight) layer of a solid substance. During this time,

though it is measured in microseconds, a part of the mesons has time to decay producing other charged particles, electrons, which are not able to pass through the layer of lead over the counters at the lower altitude.

The decisive proofs of meson decay as well as the law according to which this decay proceeds in time were obtained by entirely different methods.

First of all, it was found possible to obtain several new photographs of a meson track in a cloud chamber (Fig. 40). These photographs clearly showed the broadening end of the meson track that stopped in the gas of the chamber. Out of the end of this track came the thinner and absolutely rectilinear track of an electron (or positron) with an energy of several tens of millions of electron volts. This apparently is a very curious and hitherto unknown phenomenon: not a photon but a relatively heavy charged particle (a meson) is converted into another particle of matter* which is also charged. In this process, an extremely large quantity of energy is liberated due to a reduction in the rest mass; it appears in the form of the kinetic energy of a light particle whose velocity is so great as to be insignificantly less than that of light.

A similar type of meson decay was later studied by different physicists using the cloud chamber in a magnetic field. These experiments confirmed the view that a decaying negative meson produces an electron, and a positive meson is converted into a positron according to the law of the conservation of charge. In certain cases there was also observed a rather strange phenomenon: the charged particle stopped in the gas (argon) of the chamber was very much like an ordinary meson and did not produce any visible products of its transformation. We shall return later to an explanation of this mysterious "disappearance" of the meson.

* It will be seen later that decay produces both charged particles and neutral particles, which of course are not visible in a cloud chamber.

The fact that a meson in decaying usually turns into an electron (or positron) did not yet permit one to get a full picture of the fate of the stopped meson. It was necessary to determine how fast such a process proceeded, and to find out whether a meson could not during this time experience some other transformations. To do this, high-speed counters began to be used for the study of stopped mesons in place of the cloud chamber. They made it possible to determine very accurately the instant of passage of the meson and also of the electron that appears during decay.

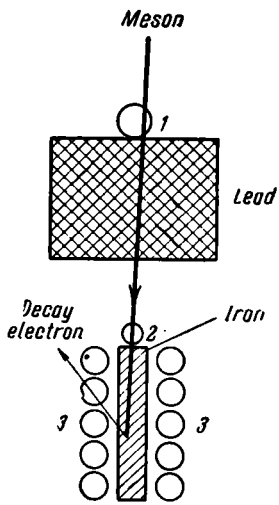


Fig. 41. A simple-type arrangement for studying meson decay. A meson can pass through counters *1* and *2* and be brought to rest in a layer of iron, where it decays, while the electron that emerges in the decay process is registered by one of the counters of group *3*

An apparatus of this type is shown diagrammatically in Fig. 41. It registers all cases of particles passing through the telescope (counters *1* and *2*) and stopping in a certain block which consists, for example, of iron. The thick layer of lead in the telescope enables all electrons falling on the telescope to be "sifted out," as in the experiment with the apparatus shown in Fig. 39. A portion of the electrons ejected during the decay are registered by one of the counters of group *3*. The principal feature of this apparatus is the special design of the electronic circuits. Here, unlike the ordinary pulse amplifier which registers only coincidence in time of the discharges of different counters, a more complex system is used. It permits measurement of the time difference between triggering of counters *1* and *2*, and counters *3* to within several ten-millionths of a second.

Numerous measurements made by this method showed that there is a delay in the response of counters *3* as compared with counters *1* and *2*. This lag, which on an average is equal to two microseconds, is found to vary slightly in different cases. It turned out that the law of meson decay

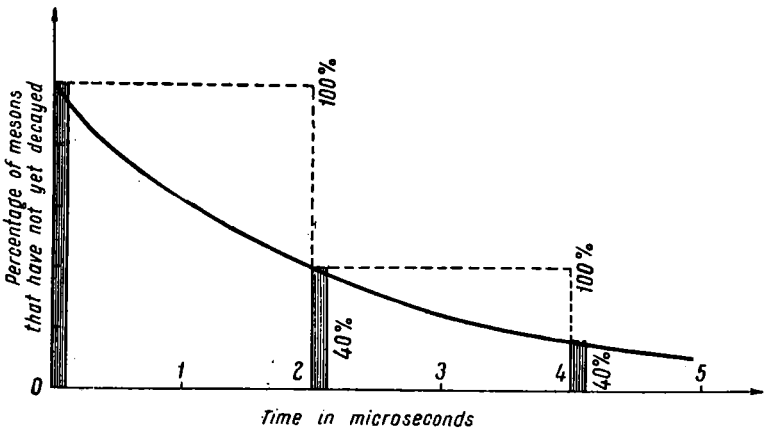


Fig. 42. The law of meson decay. The horizontal line measures the time, and the vertical line, the number of mesons that have not yet decayed. Nearly 60 per cent of the mesons "die" every 2 microseconds

(Fig. 42) is the same as that for the atomic nuclei of radioactive substances. Radioactive nuclei, it will be recalled, do not all decay at once, but gradually, so that during a definite period, called the average lifetime, only a certain and strictly definite part will have time to disintegrate. This continues an unlimitedly long time, i.e., as long as even the tiniest quantity of such nuclei remains. However, in contrast to radioactive nuclei, mesons, despite their very short lifetime, do not always have time to "die" by decay. It was found that, for example, negative mesons that have entered iron do not produce electrons at all (as also in certain cases in the cloud chamber) and, consequently,

do not "live long enough" to decay. At the end of the chapter we shall return to the fate of these particles that proved so surprising to physicists.

WHAT DO "COSMIC" AND NUCLEAR MESONS HAVE IN COMMON?

Even at the time when it seemed that the similarity between Yukawa's heavy photon and the meson of cosmic radiation was sufficient ground for identifying the properties of the predicted and observed particles, new-type mesons were discovered.

The new discovery was the outcome of further successes in the development of photographic plate techniques. In 1947, while engaged in a study of particles stopped in photographic emulsions, the English physicist C. F. Powell noticed a very characteristic phenomenon, about which some idea may be gotten from the microphotograph given in Fig. 43*a*. This photograph shows a gradually widening horizontal track of a stopped particle; from the end of this track there extends another, thinner track which also ends in the same photographic plate. Numerous observations of such cases showed that the length of the second track was always the same (about 600 microns), and this meant that it belonged to a particle whose energy is always the same (it was found to be equal to four million electron volts). The thickness of both tracks is dependent primarily on the masses of the particles that produce the tracks: the thinner track in the photographic emulsion always belongs to a lighter particle (if the two particles are compared at one and the same distance from their end, where the velocities of both particles should, as computations indicate, nearly coincide). A detailed study of such double tracks was carried out by counting the number of developed grains in the photographic emulsion per unit length of track, and also by investigating the curvatures caused by colli-

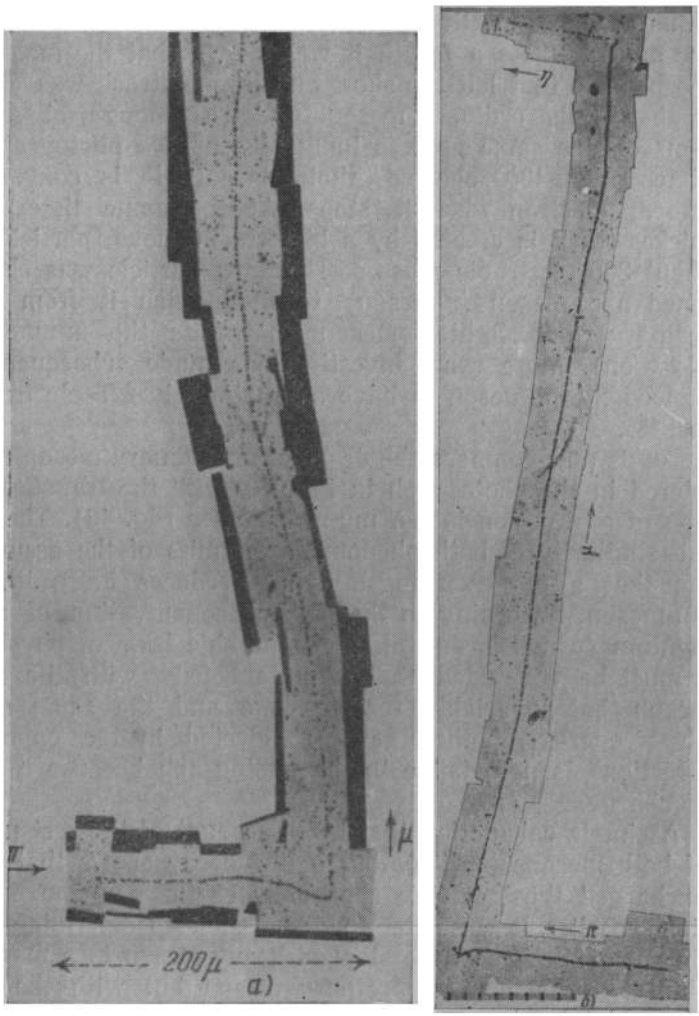


Fig. 43. a) A microphotograph of the decay of a heavy meson (π-meson) into an "ordinary" (μ-meson); b) the same process on a photographic plate that is sensitive to thinly ionizing particles; the electron (η) emerging from the end of the μ-meson track can easily be seen in the photograph

sions of the respective particles with the atomic nuclei of the emulsion. As a result, it was shown that the mass of the particle that left the short and thinner track was close to that of the ordinary meson. And true enough, observations of this same process in more sensitive photographic plates (Fig. 43*b*) showed that this particle is converted into an electron when it stops. At the same time, the thicker track is created by a hitherto unknown particle of about 300 electronic masses. This new particle was christened a pi-meson (π-meson) to distinguish it from the ordinary and lighter meson known as the mu-meson (μ-meson). More exact investigations made subsequently showed the pi-meson to have approximately 275 electronic masses.

Let us now compare the decay of an ordinary meson registered in the photograph in Fig. 40, with the transformation of a pi-meson into a mu-meson (see Fig. 43). The total similarity of both phenomena permits of the assumption that a pi-meson in decaying produces an ordinary mu-meson. According to the law of conservation of momentum (which is one of the immutable laws of physics) it must be concluded that simultaneously with the mu-meson that invariably receives one and the same supply of energy, another particle (ejected in the opposite direction) is not visible in the photograph because it has no charge.

A simple calculation that takes account of the rest mass of both mesons participating in the decay shows that this uncharged third particle can easily be the neutrino, mentioned earlier. It was later found possible to determine also the mean lifetime of the stopped heavy meson in a manner similar to that for the ordinary meson but with the aid of special luminescent counters. This lifetime turned out to be about one hundred times less than that of a mu-meson, that is, approximately two hundred-millionths of a second.

Soon after the discovery of the "heavy" meson, Powell

and his coworkers discovered in photographic plates still another phenomenon that is illustrated by the photograph in Fig. 44. Again we see the familiar track of a heavy meson that gradually thickens and curves at the end; however, in contrast to the decay case, several thicker tracks project out from its end; they obviously belong to considerably heavier particles (protons, alpha particles). These particles could arise only by disintegration of one of the atomic nuclei of the emulsion, which disintegration was the result of the absorption of a meson by the nucleus. Such absorption is found to be possible if the heavy meson has a negative charge: it will then be attracted by the positively charged nucleus before having had time to turn into an ordinary meson. Further observations established that such cases are just as prevalent as are cases of the decay of heavy mesons, and the masses of the mesons causing disintegration were found to be (within measurement error) the same as the masses of decaying pi-mesons. A similar case of nuclear disruption on the capture of a pi-meson was later detected in a cloud chamber (see Fig. 44*b*).

The discovery of new-type mesons compelled scientists to view critically the assumption that the heavy photon, or, otherwise, the nuclear meson, and the ordinary "cosmic" meson are of the same nature. There were indeed not sufficient grounds for the contention that the heavy photon and meson are one and the same particle, without having resolved two other questions: 1) Is it possible directly to knock out of atomic nuclei the very same mesons that are observed in cosmic radiation? 2) Can "cosmic" mesons be absorbed by nuclear particles (protons or neutrons), and what then takes place?

The first question studied in detail was that of the interaction of an ordinary meson with atomic nuclei.

We have already pointed out above that when negative mesons stop in an iron filter or in the argon of a cloud chamber, they do not only fail to decay (with the ejection of

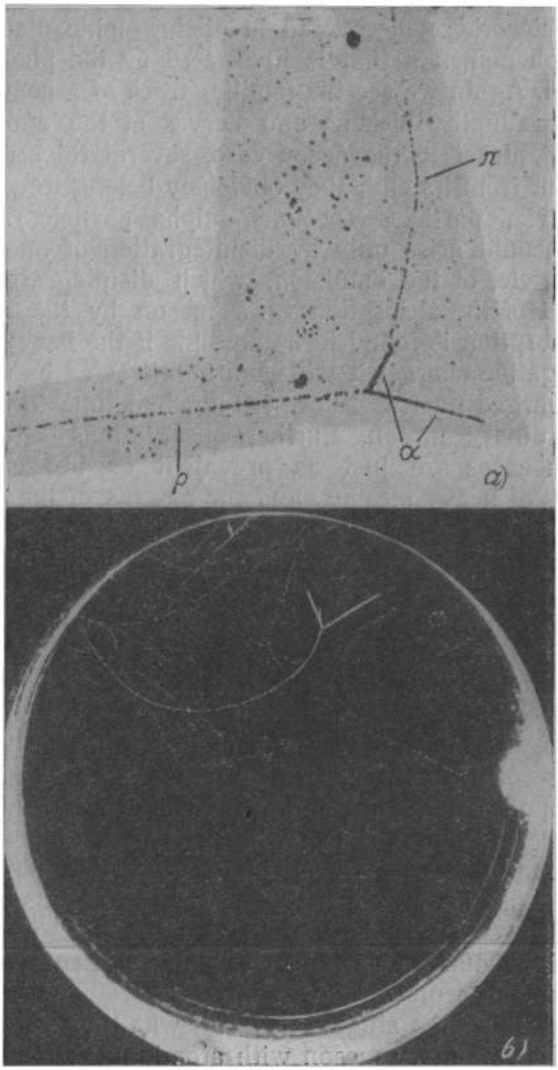


Fig. 44. *a*) Nuclear disintegration in a photographic emulsion caused by a heavy meson come to rest. The track of the meson (π) differs from the others by its slight density and the gradual thickening at the end. The remaining tracks belong to "fragments" of the nucleus that captured the meson, that is, a proton (p) and two alpha particles (α); *b*) The same process registered in the gas of a cloud chamber

an electron), they do not produce any charged particles at the end of their track at all. Continuing these studies, investigators established still another strange fact. It was found that decay does not take place only in the case when a negative meson stops near a relatively heavy nucleus. If the nucleus is light, or to be more precise, if it contains less than eight to ten protons, decay will occur. The explanation was that the meson, even when attracted directly to the atomic nucleus, does not interact very intensively with it. Only if there are a large number of particles in the nucleus and the meson is drawn near enough, does capture by the nucleus take place faster than decay. On the contrary, the meson does not react so violently with light nuclei and has time to "die a natural death," that is, by decay.

Yet, the theory which used ordinary mesons to explain interaction between particles within the nucleus inevitably arrived at the conclusion that even for the lightest nuclei the capture of a negative meson should take place many times faster than its decay. This in itself meant that one had either to reject the very basis of the existing theory of the atomic nucleus or to seek some other particle as the carrier of nuclear interactions.

And so physicists started the study of processes taking place when a heavy meson is stopped. It was established that negative heavy mesons, when stopped in matter, experience nuclear capture in all cases, thus pointing to strong interaction with nuclear particles.

The assumption that the ordinary and nuclear mesons have much in common was checked in experiments with meson decay. It was believed that an ordinary meson (like Yukawa's heavy photon) decayed into an electron and a neutrino. But the question was: How to find out how many neutral particles (and with what energy) are obtained in the decay, if not one of them had as yet been even registered by direct measurements? However, the prob-

lem was far from being hopeless. One of the variants of an experiment carried out by the writer in 1948 is explained in Fig. 45. Special electronic apparatus made it possible to register cases of stopping and decay of mesons in the absorber *A* with subsequent passage of the electrons formed through groups of counters *II* and *III*. By placing filters *F* of different thicknesses between these two groups of counters, it is possible to determine the penetrating power of decay electrons and in this way to calculate their energy.

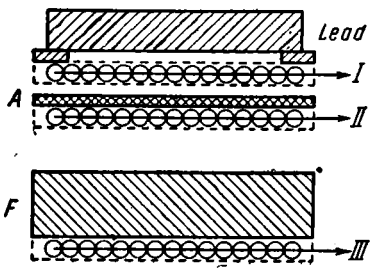


Fig. 45. An arrangement for studying electron energies during meson decay. The decay of the mesons registered takes place in absorber A (2 cm. of graphite). A graphite or lead filter *F* serves to determine the energies of the electrons from their penetrating power

It turned out that the energies of the electrons differed in different cases. This could only be explained by the fact that more than two particles are obtained in the decay, and then the energy of the decayed meson may be distributed in different ways between the electron and the remaining (neutral) particles, depending on the angle of emergence of the different particles.

One then had to conclude that the meson decays not into two, but at least into three particles, for example, into an electron and two neutrinos.

This same result was obtained later by Anderson in a more accurate measurement of the energies of decay electrons in a cloud chamber based on their deflection in a magnetic field. It then became clear that the decay process of an ordinary meson could not explain the laws of beta decay of radioactive nuclei observed in experiments.

We should now draw the conclusion that the ordinary "cosmic" meson is not directly related to the structure of the atomic nucleus and its properties. Much more closely related to this problem, however, is the slightly heavier pi-meson. Later we shall also see that mesons are not only absorbed by atomic nuclei but may be "knocked out" of them, and not only in natural reactions, but also artificially.

Chapter VI

RAYS THAT EXPLODE THE ATOMIC NUCLEUS

COSMIC RAYS AND NUCLEAR "STARS"

In 1934, Soviet scientists produced for the first time a special type of photographic plate which differed from the ordinary type by having a very thick layer of a specially prepared photographic emulsion. Using these plates, A. Zhdanov began a study of the properties of the newly discovered neutron. By directing a beam of neutrons on to a plate, the emulsion of which contains a large number of hydrogen atoms (protons), one could expect that under the impacts of the neutrons these protons would receive considerable energy, and would (in moving through the layer of emulsion) leave on the plate relatively long tracks. At first these experiments were not connected with the study of cosmic rays.

However, after developing several sets of such plates, Zhdanov noticed that in certain, though rare, cases the plates exhibited under the microscope tracks of several particles at once; judging from the density and length of the tracks, they were protons emerging with great energy from one point and forming something in the nature of prongs or a star (see Fig. 46, which shows a recent photograph of such a phenomenon). Where did these protons come from? Their total energy was such that there could be no talk of their having received it from a collision with one of

the neutrons under investigation. Here was a very fit opening for an idea expressed by Mysovsky as far back as 1932. He had suggested that precisely cosmic rays with their huge energies could be used successfully to break up atomic nuclei into their component parts, protons for instance. Protons were fully able to explain the "stars," as they are now called, that Zhdanov observed.

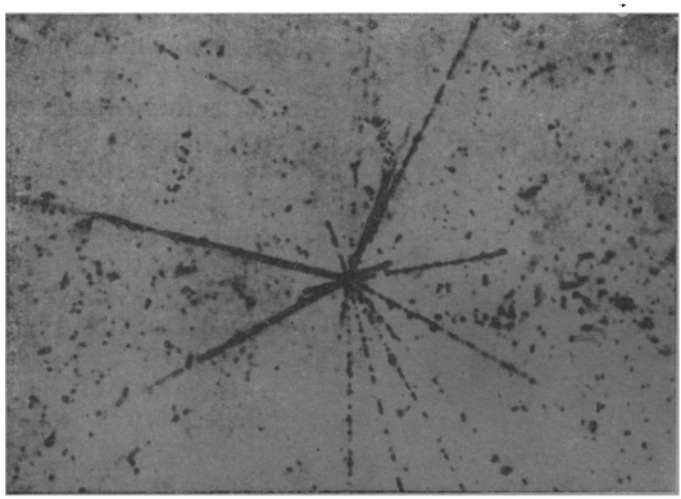


Fig 46. A "star" consisting of several protonic tracks on a thick emulsion photographic plate

To verify this guess, a set of plates was prepared and part of them were sent up to a height of nine kilometres in an aeroplane. At this altitude the intensity of cosmic rays is several times greater than at sea level. The result of this experiment exceeded all expectations. While plates on the ground recorded not more than one "star" an hour per 100 square centimetres of surface, the same type of plates at an average height of four to five kilometres above sea level exhibited 50 to 100 times as many "stars" in the same time and over the same area.

There was no more room for doubt: the plates exhibited protons knocked out of an atomic nucleus of the photographic emulsion at the very instant that a particle of cosmic radiation collided with this nucleus.

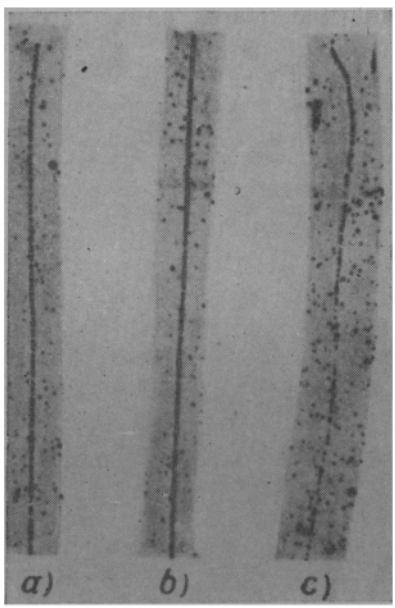


Fig. 47. The tracks of particles of different mass in one and the same photographic emulson: *a*) a proton, *b*) an alpha particle, and *c*) a meson. The difference in the density of the tracks is due to the difference in mass and charge of particles

It should not be thought that Zhdanov's plates, subjected to the action solely of cosmic rays, exhibited only "stars." On the contrary, one of the most conspicuous things in nine cases out of ten was a separate, nearly rectilinear track (similar to that shown in Fig. 47*a*) of one particle. A comparison of such tracks with the tracks obtained on the same plates during irradiation of them in laboratory conditions showed that the majority of the single tracks belong to protons possessing energies of several tens of millions of electron volts. There were also tracks of heavier particles that were often similar to the tracks left in plates by alpha particles from naturally radioactive sources (Fig. 47*b*). Lighter particles were not observed for the simple reason that the sensitivity of the photographic emulsion was at that time insufficient. Later, however, workers learned to distinguish also the tracks of particles lighter than the proton (mesons and electrons).

The general rule for differentiating the nature of particles is this: the heavier the particle passing through the plate and the greater its charge, the closer together will the individual dark grains be after development; these grains, as the microscope shows, form a track on the plate. But it should always be kept in mind that the same particle, having lost nearly all its energy, will move much more slowly and will ionize the molecules of the emulsion better. The dark grains in the tracks will then be denser. Thus, so as to be sure which particle left a given track, it is necessary that this track should end inside the emulsion. Then, knowing the energy of the particle from the length of the track, it is possible, as a rule, judging from the density of the grains, to distinguish definitely between a meson, proton, alpha particle or a still heavier particle.

This was how a convenient method was found for registering and studying cosmic ray protons emerging as a result of the fission of the atomic nuclei of the substance.

But at this very time it became clear that besides protons, atomic nuclei also contain neutrons. It then became necessary to search among the particles of cosmic radiation also for neutrons. Despite the fact that all the ordinary techniques described in Chapter II are suitable, as a rule, only for charged particles, the situation was not at all hopeless. Already in 1934, the Italian physicist Fermi carried out a number of ingenious experiments and found that sufficiently slow* neutrons are easily captured by many types of atomic nuclei, among which are the nuclei of boron. A neutron has no electric charge and so it does not experience any repulsion by the positively charged nucleus and can therefore enter it undisturbed. Inside the nucleus, the neutron is subject to strong attraction by nuclear particles (due here to nuclear forces and not electrical forces) and

* If compared to the energies of cosmic radiation, these neutrons are indeed very slow: their energy is equal to the thermal energy of the atoms of the surrounding material (usually paraffin) used as a moderator, or only a few hundredths of an electron volt.

"gets stuck" in the nucleus. A rather large amount of energy is liberated. In the case of a boron nucleus, the capture of a neutron results in the ejection of an alpha particle. Therefore, if a certain amount of boron (for example, gaseous boron fluoride) is put into an ordinary particle counter in place of the usual gas mixture, alpha particles will appear when slow neutrons enter such a counter. The charged

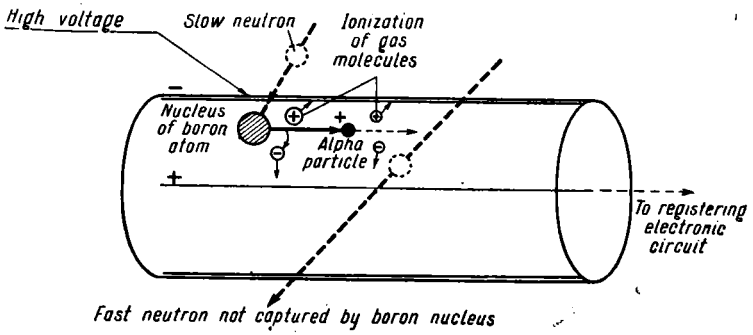


Fig. 48. How a neutron counter works. An alpha particle emerging from the nucleus of a boron atom after the latter has captured a slow neutron causes a discharge in the counter

alpha particles will cause a discharge in the counter and a large voltage pulse, thus recording the neutron hit (Fig. 48).

Careful investigations with the neutron counter described here showed that the hope of finding neutrons in cosmic radiation had proved a success. It was found that the number of slow neutrons at high altitudes increases just as fast as the number of slow protons, and fully agrees with the assumption that both particles come from atomic nuclei of air which are split by cosmic rays.

The presence of nuclear "fragments" in the form of relatively slow protons and neutrons later led Soviet scientists to a new problem. What are the particles like that are capable of causing intense fission of atomic nuclei

in solid material and in the earth's atmosphere? It was really hard to believe that electrons, positrons or photons could be such particles. Unfortunately, the first attempts in this direction were stopped during the Second World War.

Among the first in the post-war period to resume an experimental attack on this complex problem were the Soviet physicists A. Alikhanov and A. Alikhanyan. These workers aimed at making a detailed study of the composition of all charged particles of cosmic radiation at mountain altitudes. To do this, they designed and set up on Mt. Aragats, Armenia (at an altitude of 3,250 m.), a large apparatus which combined the advantages of the technique of magnetic deflection in a cloud chamber with the convenience and simplicity of counters.

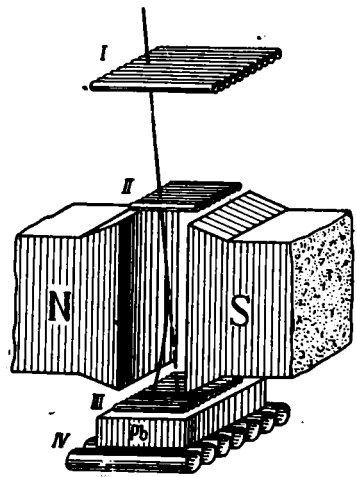


Fig. 49. The layout of one of the magnetic mass-spectrometers of Alikhanov and Alikhanyan. *I*, *II*, *III*, *IV* are different rows of hodoscope counters; Pb is a lead filter that makes it possible to determine the range of the particles. The charged particle entrant from above is deflected in the field of a permanent magnet with poles *N* and *S* and describes the arc of a circle. The degree of deflection characterizes the momentum of the particle and this together with the range enables us to determine its mass

A general idea of this apparatus, which came to be called a mass-spectrometer (since it was designed for the study of the mass spectrum of particles), may be gained from Fig. 49. The mass-spectrometer consisted of a large permanent magnet (later, an electromagnet was found to be

better) and counters arranged in several horizontal rows. A special device, usually called a hodoscope, enables one, through a system of neon lamps, to register on motion picture film the triggering of each individual counter. Each counter is connected with a neon lamp that flashes from a voltage pulse in the counter. The counters are small and when used in large enough numbers they enable one to follow closely the trajectory of a particle (hence the name hodoscope, an instrument showing the trajectory of particles) in a magnetic field and to determine from the magnetic deflection both the sign of the charge and the magnitude of the momentum of the charged particles. If in addition a particle has come to rest in one of the filters placed between the lower rows of the hodoscope, its range can also be found; thus one can likewise determine the mass of the particles, whose energy may reach as much as a thousand million electron volts.

The very first investigations carried out on Mt. Aragats in 1946-47 were convincing proof that among the positively charged particles there was an unexpectedly large number of protons (fully 10% of the total stream of charged particles), whose energy proved sufficient for the fission of atomic nuclei. The question as to the origin of these protons in the atmosphere was not yet altogether clear, although Shain's experiments, mentioned in Chapter IV, had already hinted at the close relationship between these protons and the primary protons entering the earth's atmosphere directly from outer space.

Gradual improvements in the techniques of the mass-spectrometer enabled Alikhanyan and his colleagues to carry out during recent years a still finer analysis of the composition of cosmic rays and, in agreement with other data, to show that the group of charged particles is not limited to the proton and two types of mesons (besides the electron and positron), although the nature of the other particles is still a matter of guesswork to this day.

As soon as the fission of atomic nuclei by cosmic rays was discovered, many workers, among them A. Zhdanov in the U.S.S.R. and Wambacher in Germany, began an intensive study of this exceedingly interesting phenomenon using thick photographic emulsions. Later, these same fissions of nuclei were detected by other methods, including the cloud chamber. For example, the photograph in Fig. 50 clearly shows a group of protons emerging from a lead plate in a cloud chamber; they are easily distinguished from electrons and mesons by the density of the track.

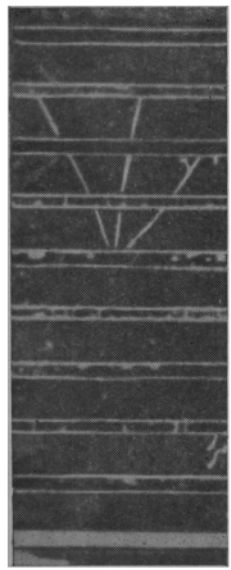


Fig. 50. A photograph showing the disintegration of a nucleus in a lead plate in a cloud chamber under the action of a particle of cosmic radiation. The tracks in the chamber belong to particles that are slow enough to produce very thick tracks and are energetic enough to pass through another lead plate several millimetres thick. These particles can only be protons

Still it was precisely photographic plates that made it possible to determine for the first time that "explosions" of atomic nuclei produced by cosmic rays are sometimes utterly different from any of the known cases of transformation of nuclei.

Indeed, outside the field of cosmic rays scientific workers have learned to change the composition of atomic nuclei of very many substances by "bombarding" them with more or less energetic, naturally or artificially obtained, particles of different types: photons, protons, alpha particles, neutrons, and others. In many cases, such nuclear reactions amount to one or, at most, two nuclear particles being knocked out of the nucleus. It often happens that the nucleus gives up the obtained energy (without losing a

single one of its own particles) either at once, by emitting a photon, or after a more or less long period by emitting an electron or positron. There are also nuclear reactions in which large "fragments" (one or several alpha particles) fly out of the nucleus. And only in three cases that concern the heaviest elements (uranium, thorium, and protactinium) can the nucleus "break up" into two large, almost equal parts, each of which in itself is a rather heavy but unstable nucleus that passes through a number of transformations producing at last the nucleus of a stable and well-known chemical element that is entirely different in properties and weight from its "parent" (for example, uranium).

When particles of cosmic radiation hit an atomic nucleus the latter may receive tens, hundreds, and thousands of times more energy than in all the above-mentioned cases. It is therefore natural that the effect may also be much stronger. Judging from observations with photographic plates, the more frequent case is fission of the nucleus with random ejection of several (usually 2 or 3) individual protons or alpha particles, as may be seen from Fig. 46. It was photographs of this type and form that led to the name "star." Such fission is usually explained as follows. A not too energetic cosmic particle hits a nucleus and (like an incandescent piece of metal thrown into a cup of water with resulting intense evaporation of the water) it forces some of the particles of the nucleus to "evaporate" rather quickly in different directions.

There are also fissions in which several nuclear particles are observed to fly out from a certain point in nearly one and the same direction. This is more in the nature of a "shower" than a "star"; in this case, the high-energy cosmic particle knocks out several nuclear particles in the direction of its motion.

But the most amazing "stars" observed in photographic plates were detected in 1939 by A. Zhdanov. It turned out that some, though very rare, "stars" appear in the form of a huge shower of many tens of protons emerging in one

direction (Fig. 51). By counting the number of protons in each such shower (approximately, since this is utterly impossible to do exactly, as may be seen from the figure), Zhdanov was able to show that their number is about the same as that of the protons in the nucleus of an atom of bromine, and, at times, as many as there should be in silver. Now recall that both bromine and silver are the most important constituents of photographic emulsion. All the other atomic nuclei that might be met with in the emulsion are much lighter than the nuclei of bromine and silver. These observations permitted Zhdanov to conclude that high-energy cosmic particles are sometimes capable of releasing so much energy in an atomic nucleus that the latter flies into "pieces," which are individual protons and neutrons. Naturally, an "explosion" of such calibre requires a tremendous expenditure of energy, tens of times more than is required in ordinary nuclear fission. But whatever the mechanism of this phenomenon, it is entirely feasible (from the viewpoint of energy expenditure) even for the majority of cosmic particles reaching the surface of the earth, and it may serve to illustrate the unthinkable potentialities latent in cosmic rays.

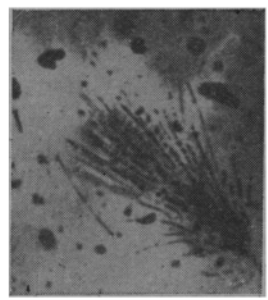


Fig. 51. A shower of tens of protons which can only be explained by the total disintegration of a rather heavy atomic nucleus (the photograph was made by A. Zhdanov).

Which of these cosmic particles usually produce nuclear fission and explosions?*

It was found from a large number of experiments with photographic plates that at not very high altitudes "stars" are formed mainly through the action of neutral particles.

* Hereinafter, for brevity, we shall call these particles "nuclear-active particles."

As the altitude increases into the stratosphere, an increasingly important role in "star" formation is played by charged particles, and at very high altitudes (28-30 km.) nuclear fission is brought about, as a rule, by the primary radiation, i.e., protons.

On the basis of all existing data, it may be concluded that in general the particles in the atmosphere that produce "stars" are chiefly protons and neutrons.* Indeed, protons and neutrons in general have equal rights in the sense of any interaction with atomic nuclei. As for pi-mesons, they decay so quickly that in the air they virtually have no time tc stop or to collide with any nucleus. And finally, ordinary mesons cannot be regarded as nuclear-active particles. As we have noted above, they are rather feebly captured by atomic nuclei and in such cases do not, as a rule, produce any nuclear fission.

The fact that in the atmosphere the processes of nuclear fission play an important part is of prime significance, for it is obvious that neutrons do not enter the atmosphere from outer space** and therefore they can arise in the atmosphere solely thrcugh the same nuclear fissions or explosions. In this way, we obtain our first indication of the presence, in the atmosphere, of a peculiar nuclear cascade, that is, a process of the successive "multiplication" cf nuclear particles. We shall shortly examine this cascade in more detail.

DECIPHERING "SPECIAL" SHOWERS

We have already examined one of the specific phenomena of cosmic rays, the cascade multiplication of electrons and photons resulting in so-called cascade showers that consist at times of a huge number of particles. However, if we con-

* A comparison of neutrons and the other neutral particles, as for example, photons, shows that the latter interact with nuclei very weakly.

** Among other things, this follows from the property of free neutrons to decay gradually, turning into protons.

sider that chiefly protons enter the atmosphere from outer space, the origin of electron-photon showers is still a riddle. We shall now relate how showers of an entirely different type were discovered and investigated in cosmic rays. With-

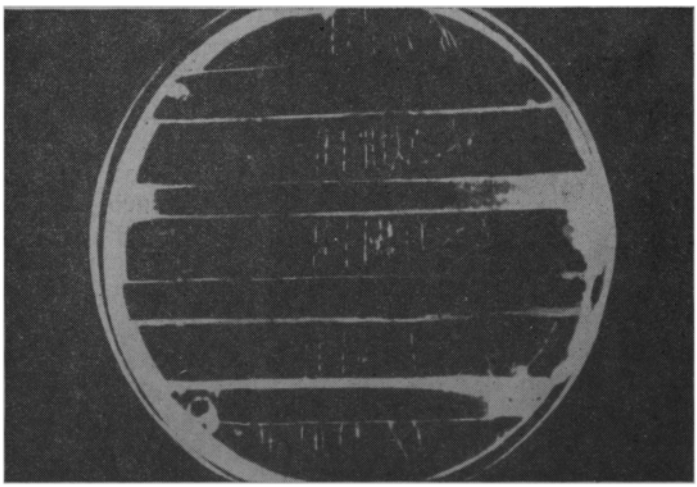


Fig. 52. One of the first photographs of "special" showers in a cloud chamber with lead plates

out these showers it is impossible to get even an approximate idea of the extreme diversity of particles observed in the earth's atmosphere.

As early as 1936 in cloud chamber experiments and somewhat later with the use of counters, showers were discovered that clearly did not resemble the ordinary electron-photon showers. Although at first the nature of these showers was not at all understood, it could be assuredly stated that they included some sort of penetrating particles, that passed through lead without the slightest "multiplication," just like mesons. One of the later photographs of such a shower in a cloud chamber with lead plates is shown in Fig. 52. Here is a clear-cut picture of a beam of particles

that do not multiply in lead. This beam is seen emerging from a definite point in the thick lead block placed over the chamber.

A similar picture of showers was also obtained on the basis of numercus experiments with counters carried out, among others, by the Hungarian physicist Jánossy and his collaborators in 1940-44.

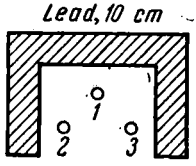


Fig. 53. An arrangement that was used to investigate "special" showers generated in lead. The showers were registered by triple coincidences of discharges in counters *1*, *2*, and *3*

The following experiment was done in 1945 in the Pamirs at the suggestion of V. Veksler. A simple apparatus (Fig. 53) that consisted of three ordinary counters connected in coincidence was used to register showers of charged particles inside a thick block of lead. The presence of showers even under a thick layer of lead was not in itself surprising. Though the electrons and photons in the atmosphere are almost wholly absorbed by lead, secondary electrons and photons are formed throughout the thickness of the lead and then "multiply." These secondary electrons and photons come from the ionizing action of mesons and their radiative collisions.

However, it was found from measurements at different altitudes that the apparatus shown in Fig. 53 registers not only secondary showers from mesons, but also some other, "special" showers. The fact of the matter is that the number of secondary showers should increase with elevation just as the stream of mesons in the atmosphere; actually, however, the number of registered showers increased much more rapidly.

With the aim of finding an explanation for this complex phenomenon, a large number of investigations with all sorts of apparatus were carried out during subsequent years in the Pamirs under the supervision of Skobeltsyn and Dobrotin.

The cloud chamber again proved most effective. It carried lead plates and was covered on top with a 15- to 20-cm.

layer of lead and placed in the field of a powerful electromagnet. By having the chamber respond only when several shower particles pass through the surrounding counters, it was possible to determine the nature of all particles passing through the chamber. The pictures of the "special" showers were quite different from a secondary shower that consists only of electrons and photons in addition to the single meson that produced them. Besides the electrons, whose trajectories are usually strongly curved due to the magnetic field, there was also observed a simultaneous passage of several particles through the lead plates without the formation of cascade (electronic) showers and without noticeable deflection of these particles in the magnetic field. In addition, such a shower rather frequently had the thick tracks of heavily ionizing particles that resemble "fragments" from nuclear disintegrations. These "fragments" usually appeared not at the site of formation of the basic shower, but below it, for example in the gas of the chamber; and it often seemed that they were not in general related to any one of the charged particles of the shower. It was obvious that all these events had nothing to do with the secondary showers from mesons. An example of a typical photograph of a "special" shower is shown in Fig. 54.

In order to understand the nature of the penetrating particles of "special" showers that do not multiply in lead, detailed measurements were made of the deflecting action of a magnetic field on these particles inside a cloud chamber. The full range of the particles in a material placed under the chamber was also measured. As we have already pointed out, a knowledge of these two characteristics is sufficient to determine the mass of the particles. And it turned out that in addition to mesons, there were also appreciable quantities of protons among the penetrating particles. However, the measurements were not accurate enough to indicate what type of mesons were present, the ordinary variety or the heavy type.

The next step in the study of these particles that comprise "special" showers is connected with the use of photographic plates. After Powell and his collaborators had learned to determine the mass of individual particles from

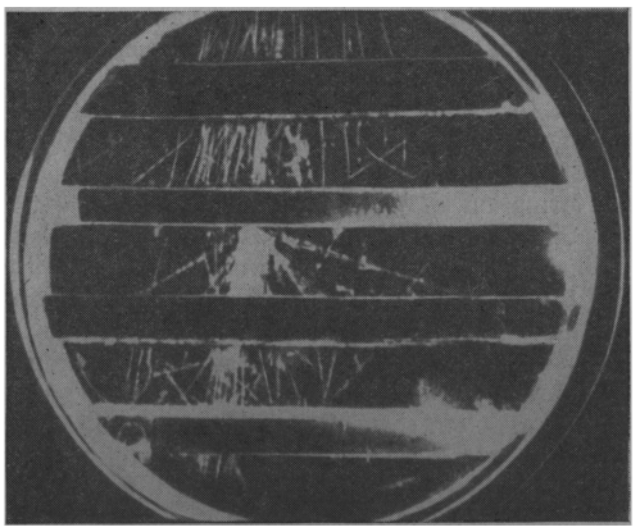


Fig 54. A typical photograph of a "special" shower; three types of particles may be distinguished: electrons that produce cascade multiplication in lead, penetrating particles, and heavy nuclear fragments

scattering by the atomic nuclei of a photographic emulsion (this was in 1948-49), they applied their method also to the particles of "special" showers. The point is that in Powell's plates these showers differed sharply from ordinary "stars" by the more or less directed beam of fast particles that do not resemble the slow "fragments" of an atomic nucleus, protons, or alpha particles, which are also present in the formation of "special" showers (see, for example, the microphotograph in Fig. 55).

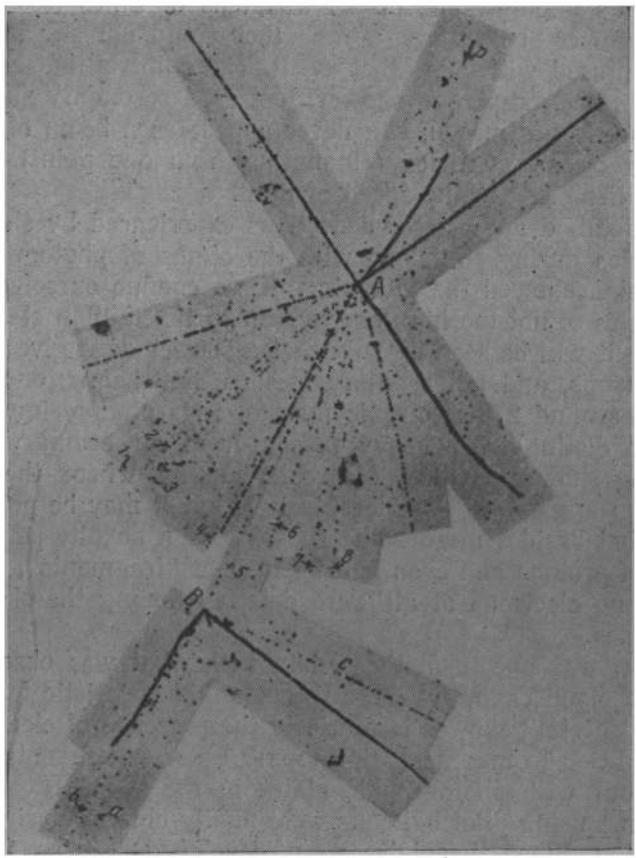


Fig. 55. A microphotograph of a "special" shower in a high-sensitive photographic plate. The shower arose at point *A* due to the collision of a very high-energy proton (*p*) from above and an atomic nucleus. *1, 2, 3, ..., 8* are fast particles that comprise the shower: heavy pi-mesons and high-energy protons; one of these particles (*5*) produces in its movement a new nuclear explosion at point *B* with the ejection of two heavy "fragments" and three fast particles (*a, b, c*)

Despite the fact that the number of showers observed in Powell's photographic plates was tens of times less than the number of ordinary "stars" they could not any longer be confused with any other event. The point is that an ordinary electron-photon shower, just as a secondary shower produced by a meson, can never appear as a beam of thin tracks of fast particles (emanating from one point) with velocities close to the speed of light.

A detailed analysis of deflections experienced by shower particles during collisions with the atoms of photographic emulsion showed the following. If we confine ourselves to particles of not too high energy (up to 150 million electron volts) it will be seen directly that a shower does give birth to mesons, and not ordinary mesons, but heavy ones of mass around 275 electronic masses. It is already impossible to distinguish a heavy meson from an ordinary one among shower particles of greater energy where the deflection angles are considerably less, but it may be pointed out that besides mesons the shower has a definite percentage of protons and even heavier nuclear "fragments"; however, no electrons at all were detected among the shower particles.

How was one to fit these data with what was observed in the cloud chamber where the most characteristic feature of a "special" shower is precisely the presence of electrons in addition to mesons (or protons)? Later experiments carried out with photographic plates in the stratosphere (at 23 km.) using pilot balloons were finally able to clarify the question. When the plates were developed it was found that in some showers there suddenly appeared near the spot of the main "explosion" a pair of particles emerging in the same direction as all the shower particles, at a relatively small angle to each other. A detailed study of these pairs showed them to be the familiar electron-positron pairs produced by photons which move together with the beam of charged shower particles. And that is not all, a measurement of the energies brought in by such photons elicited a

very curious fact. Photons of energy less than 70 million electron volts were rather rarely observed, although in ordinary cascade showers low-energy photons, on the contrary, are clearly predominant in number.

A comparison with other experiments carried out somewhat earlier by other physicists in entirely different conditions* led to the following conclusion. It was found that photons could appear not only during the deceleration of any charged particles, but also in the decay of a special type of neutral particle, viz., neutral mesons whose mass is slightly less than the mass of a pi-meson and whose lifetime is at least a million times less. In this case, each neutral meson decays into two photons, and if we take account of the well-known relationship between the mass and the energy of a particle, it will be found that in the decay even of a slow meson each of the photons should receive an average energy of not less than 70 million electron volts. This energy is quite sufficient to create an electron shower of the cascade type if the photon passes through, say, lead.

The experiments described here plus a large number of others revealed the following. The so-called "special" shower is a peculiar type of explosion of the atomic nucleus, which gives rise not only to nuclear fragments, protons and neutrons, but also to a certain number of high-energy mesons, both charged and neutral. The decay of neutral mesons produces photons which in turn produce new, and this time pure, cascade showers of the electron-photon type. Protons, neutrons and heavy charged mesons pass through matter and collide with atomic nuclei causing disintegration accompanied by the emission of new nuclear fragments, but this time of low energy. And finally, if the birth of a "special" shower takes place in the air, all the heavy mesons quickly decay into ordinary mesons, which now do not produce any new nuclear disintegrations at all and pass

* These experiments, which will be described shortly, were performed with artificially accelerated charged particles.

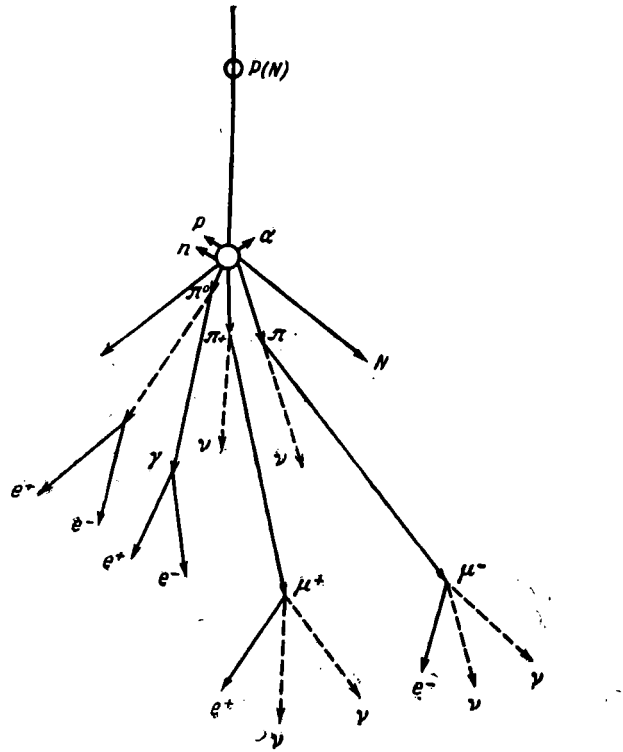


Fig. 56. A series of processes that accompany the formation of electron nuclear showers involving atomic nuclei of air under the action of a proton (P) or neutron (N) of high energy (thousands of millions of electron volts). p, n, α are protons, neutrons, and alpha particles ejected by the atomic nucleus; π^+, π^- and π° are the positive, negative and neutral pi-mesons; μ^+, and μ^-, are the positive and negative mu-mesons; $e+$ and e^- are positrons and electrons; γ is a photon; and ν is a light neutral particle (neutrino)

through big thicknesses of matter without further "multiplication" and appreciable loss of energy.

When the nature of "special" showers was deciphered, it became possible for the first time to study the process during which electrons appear in cosmic rays. This process was found to be connected with profound changes of atomic nu-

clei. For this reason, these "special" showers now received the name of "electron-nuclear" showers. The general scheme of the processes that accompany the origin and development of the electrons of a nuclear shower is given in Fig. 56

THE NUCLEAR CASCADE AND EXTENSIVE AIR SHOWERS

Now let us examine the origin of electron-nuclear showers in matter. First of all, it is obvious that they are caused by particles of very high energy: calculations of the total energy released in the generation of an average size shower of this type show that it must be in the thousands of millions of electron volts as compared to the hundreds of millions required to produce an ordinary "star." And that is not all, special experiments carried out at different geographical latitudes showed that particles generating electron-nuclear showers are but very slightly affected by the earth's magnetic field. This means that their energy should, in the majority of cases, exceed 20,000 million electron volts.

What is the nature of these powerful "shells" that disrupt atomic nuclei? Numerous experiments with photographic plates show that at mountain altitudes they may be both charged and uncharged particles; in the stratosphere they are mostly charged particles. Observations of electron-nuclear showers conducted under thick layers of lead show that these particles cannot be electrons or photons since both are too readily absorbed in lead. On the other hand, the sharp increase in number of showers with altitude shows that the particles responsible are absorbed in the atmosphere much more readily than ordinary mesons. They cannot be heavy mesons either since the latter decay in air very quickly.

We are left with the conclusion that electron-nuclear showers are produced by nuclear particles, protons and neutrons. This was brilliantly confirmed by experiment. The presence of high-energy protons in the atmosphere was no

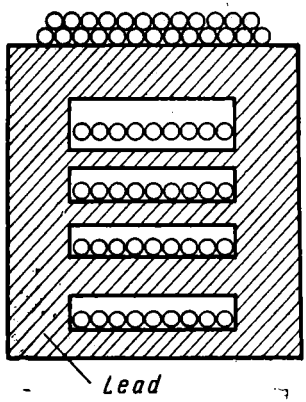


Fig. 57. One of several variants of a hodoscope arrangement for investigating electron-nuclear showers (Lyubimov). Each circle is a counter connected with a corresponding neon lamp

longer doubted after it was found that they comprised the principal part of the cosmic radiation coming from outer space. Now where do high-energy neutrons come from?

Before answering this question let us digress for a moment and describe another instrument that was widely used in the Pamirs for studying electron-nuclear showers. It is the already familiar hodoscope, which in this case consists of several rows of counters divided by layers of lead of different thickness (Fig. 57). Through a special electronic circuit, which responds only when an electron-nuclear shower is generated in the hodoscope, neon lamps connected with the counters give a vivid picture of the birth and development of a shower as it passes through matter, as is illustrated, for example, by the photograph in Fig. 58. It should be noted that the hodoscope has advantages over the cloud chamber in being able to follow the development of the shower in large quantities of matter. In experiments with the hodoscope, it was possible to observe many cases when particles (including both charged and neutral) generated in an electron-nuclear shower were able in their turn to produce similar-type showers in matter. It was thus shown that the high-energy nuclear processes under study could be somewhat cascade-like. However, this nuclear cascade differs sharply from the cascade multiplication of electrons and photons which is determined only by electromagnetic processes in the vicinity of atomic nuclei and is utterly unrelated to transformations of the nuclei themselves.

Despite this difference, there was a closer relationship between the two types of cascade processes than could at first be supposed. First of all, it was found that the appearance of an electron-nuclear shower is rather frequently accompanied by the passage of an extensive air shower of electrons and photons. And on the contrary, there began to be found in extensive air showers particles capable of producing nuclear processes within thick layers of lead. Both these facts hinted at the idea that by itself an extensive shower in the air should not necessarily be caused by a very high-energy electron or photon impinging on the top border of the earth's atmosphere. It could also be a proton of the same high energy producing in the upper layers of the air an electron-nuclear shower of great power. The electrons and photons generated in this shower are fully capable of initiating an extensive air shower through subsequent positron-electron pair production and the emission of collision radiation. Not only that, it is precisely this character of extensive shower formation, as was first

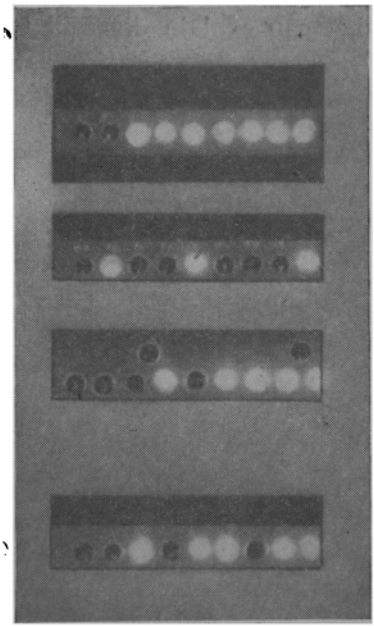


Fig. 58. A photograph obtained by the arrangement shown in Fig. 57. The lighted neon lamps show the trajectories of all charged particles passing through the corresponding counters and lead. This photograph shows how the nuclear-active particles that make up the shower have created in the lower layers of the lead a new nuclear explosion

shown by the young Soviet physicist G. Zatsepin, that can explain different types of "anomalies" in the be-

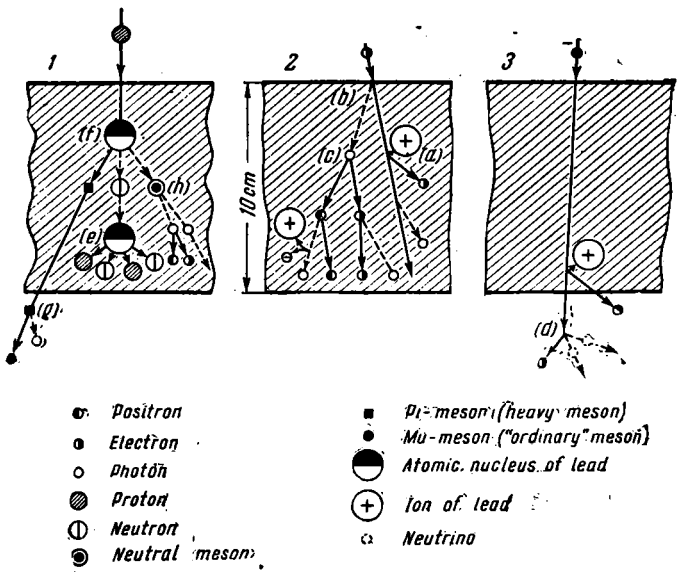


Fig. 59. Particles observed in the lower layers of the atmosphere. The total radiation consists of a nuclear-active (*1*), an electronic (*2*), and a meson (*3*) component. Shown in the diagram are the principal processes involving these particles as they pass through matter: (*a*) ionization of the molecules of the substance; (*b*) radiation collision of photons by electrons and positrons; (*c*) electron-positron pair production by photons; (*d*) mu-meson decay into an electron or positron and two neutral particles; (*e*) the disintegration of atomic nuclei; (*f*) the formation of electron-nuclear showers; (*g*) pi-meson decay, and (*h*) neutral meson decay

haviour of extensive air showers, which are impossible to understand from the viewpoint of ordinary cascade theory.

As we have already seen in Chapter III, Vernov's investigations in 1949 were the culmination of a big series of experiments devoted to the study of the composition of cosmic rays entering the stratosphere from outer space. About this time, the picture of cosmic radiation in the lower layers of the atmosphere was also clarified. And it turned out that here radiation consisted of an extremely "variegated," and at first sight, even chaotic conglomeration of electrons (and positrons), photons, mesons (both "ordinary" and heavy), and, finally, of nuclear fragments (protons and neutrons) possessing the most diverse energies (Fig. 59). The problem that now clamoured for a place on the "agenda" was to investigate how a stream of primary protons, despite the stupendous energy of the particles and the lack of any appreciable energy losses in the production of cascade (electron-photon) showers, succeeds in changing beyond recognition so quickly. Indeed, already at an altitude of about 20 km., the predominant part of the whole flow of particles consists not of protons of energy in the thousands of millions of electron volts, but of electrons and photons with a mean energy of "only" hundreds of millions of electron volts. To resolve this question, Vernov suggested to his colleagues to build hodoscopes that could be sent up into the stratosphere in sounding balloons to register showers produced by primary cosmic rays in lead.

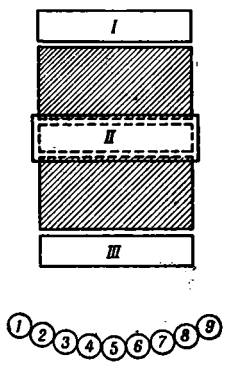


Fig. 60. A hodoscope layout (Charakhchyan) used in the investigation of shower formation in lead at high altitudes

Fig. 60 shows the arrangement of such an apparatus. Lead is placed between counters *I, II* and *III*. The triggering of each individual counter (*I, II, III, 1, 2, 3*, etc.) was re-

corded not by photographing flashing neon lamps, but by a rather complex system of telemetering the signals.

If we detected shower formation in sufficiently thick layers of lead at different altitudes in the stratosphere, it could be stated that in this case it was not cascade multiplication of air electrons in lead. It was established that, like the phenomenon of electron-nuclear showers studied at low altitudes, there takes place in this instance a very intense generation of electrons and penetrating particles of high energy in lead. And secondary showers from mesons at high altitudes now play hardly any role, so that electron-nuclear showers could be observed in the "pure" state.

The data obtained was carefully analysed and correlated with the results of other experiments. It was found on the one hand that the number of observed showers increased with altitude according to the same law as the number of high-energy protons, and on the other hand, that the number of showers was sufficiently great to explain the origin of the entire electron-photon component in the stratosphere. As to mesons, it was already possible to state, on the basis of properties of electron-nuclear showers studied at low altitude, that they are born in the very same showers, although it was still impossible to draw the appropriate quantitative conclusions.

Thus the new investigations of Vernov and coworkers showed how such rapid absorption of protons takes place in the upper layers of the atmosphere and that at low altitudes secondary radiation is almost exclusive and consists mainly of electrons and mesons.

This, together with the investigations of the Pamir team of physicists described in this chapter, was the key to the solution of the most important problem in the science of cosmic rays—the problem of the interaction of cosmic rays and matter.

HAVE THE ELEMENTARY PARTICLES OF MATTER A STRUCTURE OF THEIR OWN?

A little over 40 years has passed since physicists first succeeded in probing the depths of the atom and in understanding its internal structure, which resembles a miniature solar system (the "planetary" model of Rutherford). A little over 20 years has passed since the structure of the atomic nucleus itself with its protons and neutrons became the subject of investigation. We might now ask whether one should expect the proton and neutron, in their turn, to be complex particles consisting of some other smaller units, as yet unknown to science. Can we not regard the concept "elementary particle" as reflecting only that limit of divisibility of matter that the science of the structure of matter has at this stage reached?

To show how one may approach these questions, we shall draw an analogy between the phenomena whose study helped to reveal the structure of the atomic nucleus, and the properties of those elementary particles which comprise the secondary cosmic radiation. Very important for an understanding of the structure of atomic nuclei are various types of nuclear transformations, including both the spontaneous type (radioactivity) and the induced type (nuclear reactions), that is, caused directly by the action of particles of sufficiently high energy. Recall now that also elementary particles in cosmic rays undergo numerous transformations, some of which resemble radioactivity (the spontaneous meson decay), and other nuclear reactions, as for instance the conversion of a photon into an electron-positron pair in the electric field of an atomic nucleus.

However, this analogy in itself is not yet ground enough for one to speak of a complex structure of "elementary" particles, for the radioactive decay of certain nuclei that emit electrons (or positrons) is not yet proof that these electrons are a part of the nucleus. And likewise the decay of a mu-meson into an electron and two neutrinos does not at all

mean that a meson may be visualized as a complex system composed of an electron and a neutrino.

Let us now recall in what way atoms with close atomic weights differ.

If, for example, we compare atoms of ordinary hydrogen and heavy hydrogen (deuterium) it will be found that the second may be obtained from the first by adding one neutron to the nucleus of the atom. An increase in the number of particles in the nucleus leads to an increase in the size of the nucleus just as an increase in the number of electrons increases the size of the atom as a whole. Until very recently it was thought that in the field of elementary particles the situation was quite different. Although in an atomic nucleus there is, aside from the actually existing protons and neutrons, a meson field, that is, mesons in a special, "virtual" state, no addition of new mesons can alter the number of basic nuclear particles. Such an addition, it would seem, could lead only to a nuclear disintegration, that is, to a division of one complex nucleus into several simpler ones.

It was only recently that physicists detected in cosmic rays particles of a special type that became known as hyperons. This can be interpreted in a certain sense as the result of the "union" of a proton or a neutron with one or several mesons. This was how it happened. While studying the properties of particles that make up electron-nuclear showers, the English physicists Rochester and Butler, using a cloud chamber, discovered, as early as 1949, a peculiar phenomenon well illustrated by a later photograph given in Fig. 61.

This photograph shows the appearance of two charged particles emerging from a single point in the gas of the chamber somewhat like the particles of the electron-positron pair shown in Fig. 21. A detailed study of the angle of divergence of the particles of the unusual pair and a determination of their masses showed that in this case the pair does not consist of an electron and positron but of a proton and a negative pi-meson. And the primary particle cannot in any way be a photon, while the process itself does not at all de-

pend on the density of the material and could take place even in a complete vacuum. Further experiments of other workers showed that the newly discovered phenomenon is

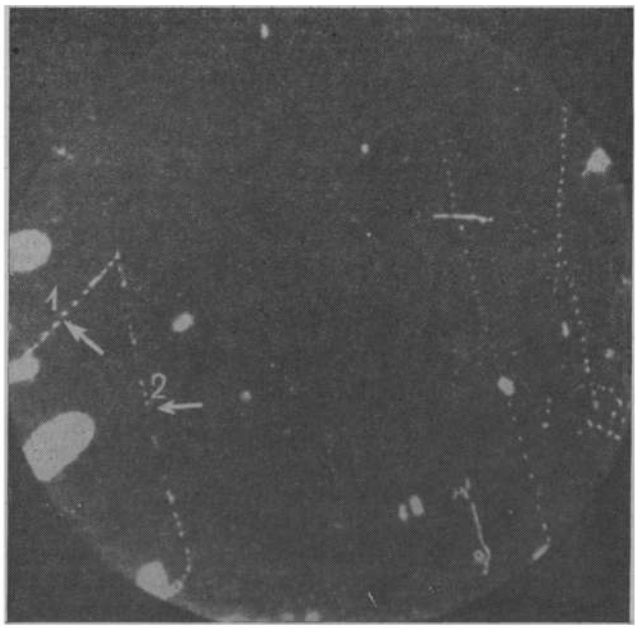


Fig. 61. Hyperon decay in a cloud chamber. *1* —left track, apparently belongs to a proton; *2*—right track, that of a negative pi-meson.

the decay of a hitherto unknown neutral particle of mass about 2,200 electronic masses, that is, considerably heavier than a proton or neutron.

The very fact that an ordinary, completely stable nuclear particle (proton) can appear from the decay of some other, unstable and heavier, particle, made physicists curious about the properties of the newly discovered particle. Despite the fact that this particle is observed in electron-nuclear showers somewhat rarely, during recent years laboratories in

different parts of the world have obtained several hundred photographs of the decay of such particles.

However, the most important data concerning the properties of these particles do not concern the decay process, but rather the process of their birth. At first it seemed that these particles could form only in nuclear interactions of very high energy. Indeed, the well-known relationship between mass and energy of the relativity theory shows that a mass equal to that of the electron corresponds to an energy of roughly one half million electron volts. Hence, the formation of a pi-meson (which has a mass equal to 275 electronic masses) requires the expenditure of nearly 140 million electron volts of energy, that of a particle of mass 2,200, over 2,000 million electron volts. In determining the energy of showers that contain the new 2,200 particles, it was found that the energy expended on them does not differ sharply from the energy required for the formation of pi-mesons. More accurate experiments conducted later with artificial cosmic rays* have shown that the necessary expenditure of energy corresponds only to the difference between the mass of the new particle (2,200) and that of the proton (1,840), that is, about 400 electronic masses. This suggested that in reality there took place not the formation of a new particle, but only the transfer of one of the nucleons of the nucleus from the ordinary state to a new state in which the energy of internal motion, and correspondingly the mass, increases nearly 20 per cent.

Thus the process of the birth of this particle resembles the process of excitation of an atom: if a definite excess of energy is imparted to an ordinary stable atom, it can retain this excess a certain time, after which it reverts to the normal state, releasing the excess energy in the form of a photon. For this reason, the new particles were called hyperons to emphasize that they are strongly excited and therefore unstable states of nucleons which can convert, relatively slow-

* These rays will be dealt with in Chapter VII.

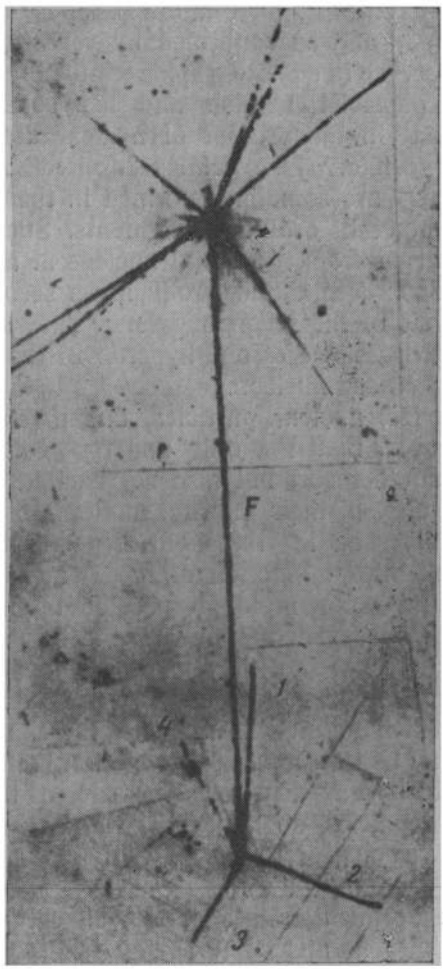


Fig. 62. The decay of an excited nuclear fragment *F* in a photographic emulsion. The energy released in the secondary "star" (rays *1*, *2*, *3*, and *4*) is due, apparently, to the transformation of a hyperon into an ordinary nucleon

ly into ordinary nucleons, liberating the excess energy this time not in the form of a photon, but in the form of a meson.

This explanation was confirmed by yet another process which was observed in a photographic emulsion by the prominent Polish physicist Danish and his collaborators. It turned out that in the process of nuclear disintegrations, produced by cosmic rays, so-called "excited" nuclear fragments (Fig. 62) are sometimes formed in the nuclei of the emulsion in place of ordinary fragments. Such an excited fragment emerges from the initial nucleus at a small speed and is very soon decelerated, producing a second "star." A careful analysis of the secondary "star" shows that its origin lies in the presence of one hyperon in the fragment in place of an ordinary nucleon.

To summarize, nuclear particles, due to some still unknown processes, may not only undergo conversion into particles of another sort but also be "excited," that is, increase the energy of their internal motion. In other words, we find ourselves on the threshold of penetrating into the secrets of the internal motion of the elementary particles of matter, and it is now no longer possible to put in absolute opposition the energy of motion and the rest energy of elementary particles. We do not yet know what determines the nature of the internal motion of these particles, though we do know that it is possible to influence the character of this motion. It may be that the internal motion includes to some degree the element of mechanical transfer of the individual parts of the particles, so that the latter can no longer be regarded as "elementary" (i. e., indivisible) in the full sense of the word.

Existing experimental data do not as yet give grounds for an unambiguous answer to the questions put at the beginning of this section. However, it may be supposed that further study of the processes of formation and decay of particles in high-energy nuclear interactions will bring us right up to problems dealing with the structure of the so-called elementary particles.

THE HEAVY SHELLS OF "COSMIC ARTILLERY"

In 1948, when physicists no longer had any doubts that the primary cosmic rays consist of protons, there appeared in the scientific press unexpected announcements adding to the already rich "storehouse" of cosmic radiation entirely new particles. The American scientists Bradt, Peters and others sent up thick photographic emulsions in pilot balloons to an altitude of 28 km. On development, these plates showed rather long tracks that were much "thicker" than any of the usually observed tracks and had a large number of tiny "branchlets" which were obviously connected with frequent dislodging of electrons from surrounding atoms. A characteristic microphotograph of such a track is shown in Fig. 63. Compare it with the track in Fig. 16 (p. 35) and you will at once see that this is an entirely new phenomenon. Indeed, although ionization produced by any charged particle is the greater, the less its velocity and the greater the magnitude of its charge, it is easy to conclude in this

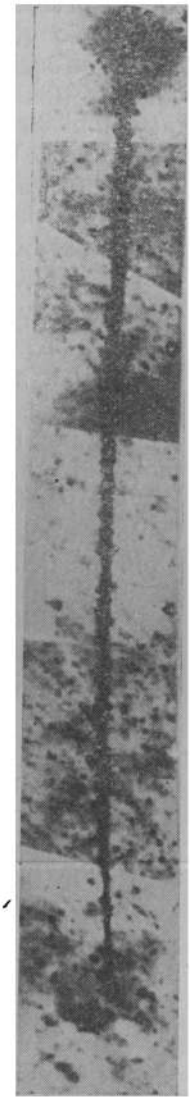


Fig. 63. A characteristic track of a heavy nucleus in a photographic emulsion obtained at an altitude of over 25 km. The photograph exhibits a large number of tiny branchlets from the track, which are created by electrons knocked out of the atoms of the surrounding substance. The gradual thinning out of the main track is due to electrons "collecting" on the nucleus as the latter slows down. The initial charge of the nucleus (as it enters the emulsion) is approximately fourteen times that of a proton; thus it is more in the nature of the nucleus of a silicon atom

case that the extraordinary density of the track and hence also the great ionization are not connected, as is usually the case, with a small speed. This is also seen in the extreme length (at times exceeding one centimetre!) of the tracks of such particles in the photographic emulsion. Because of this great track length, there can be no talk of having simply "caught" a particle of ordinary charge at the end of its flight. This is also indicated by the type of electronic "branches" around the main track: calculations show that such "branches" of electrons of relatively high energy may be created by a basic particle moving at a speed close to that of light. The abnormal density of the track can only be explained by the big charge of the particle. Comparison with alpha particle tracks from radioactive sources have shown that although ionization ought to increase with the square of the charge, individual particles should be ascribed a charge of 10, 15 and sometimes even 25 and 26 times the single charge of a proton or electron!

What particles known to physicists might be examined to explain tracks like those in Fig. 63? Since the proton and alpha particle, which have been studied repeatedly, are respectively the atomic nuclei of the chemical elements of hydrogen and helium, the newly discovered particles obviously ought to be related to heavier atomic nuclei. The size of the charges of these nuclei increases, as we proceed through the periodic system of elements with increasing atomic weights, and is determined, it will be recalled, by the number of protons in the given nucleus. In ordinary terrestrial conditions, the big positive charges of heavy atomic nuclei do not in any way manifest themselves, since they are neutralized by the negative charges of the surrounding electrons. However, long ago scientists studying the spectral composition of light from the sun and stars found that the atmosphere of celestial bodies often contains atoms of iron, calcium, silicon, and other elements, that have lost many of their electrons, and consequently, carry a big positive charge. This fact is explained by the tremendous temperatures

and hence the huge energies of the atoms which are peculiar to the sun and stars.

It is not surprising then that at the titanic energies possessed by cosmic radiation, atoms may even lose all their electrons. Certain theoretical considerations show that even if this does not happen to them outside the earth's atmosphere, still, when coming into it at tremendous speeds, they must have all their electrons shuckled off when they pass through the very first layers of the atmosphere. And, on the contrary, as these heavy nuclei quickly slow down (because of huge energy losses in ionizing air atoms) they should gradually "collect" electrons from the surrounding matter, as is so clearly seen in Fig. 63. As the track comes to a stop it becomes less and less dense, which is an indication of a decrease in the charge carried by the particle.

One should not be surprised that heavy nuclei (as all particles of the primary cosmic radiation that are heavier than the proton are usually called) were discovered only after nearly forty years of research. First of all, they make up an extremely small portion of the primary radiation: if we speak of nuclei with not less than a threefold charge, then only several are found per thousand incident protons; and only alpha particles, which are doubly charged, are met with much more frequently (on an average of one alpha particle per four to five protons). But the chief reason for the discovery being made after so many years is not this: due to the tremendous energy losses through ionization of air atoms and intensive nuclear interactions, the heavy nuclei are virtually absorbed *in toto* already at altitudes where the pressure of the air column traversed is but 1% of normal atmospheric pressure.

Further investigations with photographic plates, confirmed by experiments with the cloud chamber raised also to nearly 30 km., are in full agreement with the original assumption concerning the nature of the newly discovered particles. A comparison was made of the relative number of different nuclei, and it was found that different chemical elements are represented in this group with approximately the

same prevalence that they are found throughout the universe. Protons, for example, are no exception to this general rule because it is well known that hydrogen is the most abundant substance in cosmic space. Another rather frequently occurring element is helium, which is doubtless the origin of alpha particles that make up part of the primary radiation. Carbon, oxygen and nitrogen, which play such an important role in the atmosphere and the organic life of the earth, are hundreds of times more rare.

The abundance of the other elements gradually falls off as their atomic weights increase so that elements heavier than iron are found only in absolutely negligible quantities; and in the cosmic rays too they have not as yet been detected in perceptible quantities.

Chapter VII

ARE COSMIC RAYS OF ANY PRACTICAL USE?

In the preceding chapters of this book we learned about the nature and properties of cosmic rays, about the principal phenomena and processes that occur when these rays pass through the earth's atmosphere and in general through different substances. But probably every person who opens this book asks himself two very topical questions:

1) What is the source of cosmic rays in nature and is it not possible to obtain them artificially?

2) Of what importance is the study of these rays to present-day science and technology?

And although at present far too many difficulties arise when we begin to answer these questions, still we shall make an attempt in this chapter.

To avoid any misunderstanding it is worth emphasizing once more the necessity of differentiating clearly between true cosmic rays, or primary rays, and the rather complex combination of secondary rays of different types and extremely diverse energies that arise in the earth's atmosphere under the action of the "real" cosmic rays.

ARTIFICIAL PRODUCTION OF COSMIC RAYS

As we have already seen, despite the extreme wealth and peculiarity of the phenomena that take place in cosmic radiation, the source of all these processes, in the form of a

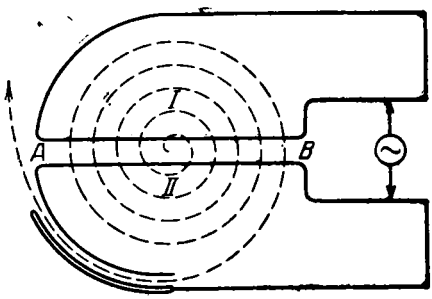
primary and truly cosmic radiation, are atomic nuclei, and above all, the nuclei of hydrogen (protons) which are so well known to physicists in terrestrial conditions.

The primary cosmic rays differ from the familiar atomic nuclei of terrestrial conditions by only one numerical characteristic—the magnitude of energy; but here the well-known law of dialectics concerning the transition of quantity into quality becomes operative. In our case, the stupendous energy of the cosmic rays is the reason for these familiar particles being endowed with wholly new properties, which during the first stages of investigation sometimes seem mysterious. But this means that physicists will reproduce and investigate in their laboratories all the phenomena discovered in cosmic rays as soon as they are able to impart the required energies to different atomic nuclei. It turns out that despite the tremendous values of these energies, such a problem seems entirely practicable and even partially solved if viewed from the engineering possibilities of today.

The point is that during recent years big progress has been achieved in obtaining artificially accelerated charged particles of high energy. This is usually done in a machine first proposed as early as 1930 by the American Lawrence, but improved considerably through an idea expressed by V. Veksler in 1944.

This machine, called the cyclotron, is shown diagrammatically in Fig. 64. A flat box consisting of two semi-circular parts (dees) is placed in the field of a huge magnet. In the centre of the cyclotron is some source of charged particles, as for instance protons or alpha particles. An alternating electric potential of several tens of thousands of volts is applied between the dees. This voltage accelerates all particles that find themselves in the gap between the dees, and the magnetic field whirls them about so that they begin to describe circles, periodically passing through this same gap. If the frequency of the alternating electric potential is such that it coincides with the frequencies of the revolution of the

particles in the orbits,* the same electric field may be used to gradually speed up the charged particles to very high energies. The improved machines based on Veksler's principle and existing in several different versions (the so-called synchrocyclotrons, synchrotrons, proton synchrotrons, and so forth) at present enable protons and other particles to be obtained at energies in the thousands of millions of electron volts, which is several thousand times greater than could be obtained just by racing them once in the highest attainable electric field. A great advantage of these sources of "nearly cosmic" rays is first the large uniformity of radiation both as to composition and energies of the particles, and, secondly, the considerable intensity which enables sufficiently frequent repetition of phenomena that are observed in the study of cosmic rays only in individual and very lucky cases.



Rig. 64. The structural features of the cyclotron. *I* and *II* are the dees to which is applied an alternating electric field that accelerates the charged particles in the gaps *A* and *B*. A magnetic field perpendicular to the plane of the drawing compels the particle undergoing acceleration to move in circles with an increasing radius (the dashed line)

In order to show in more detail the sizes and possibilities of modern accelerators designed to produce artificial cosmic rays** we give here (Fig. 65) a general view of one of these machines. As may be seen from the illustration,

* Calculations show that this frequency changes but slightly with variations in the speed of the particle. This is due to an increase in the radius of the described circle.

** It was precisely for this reason that one such machine built in the U.S.A. at Brookhaven received the name of "cosmotron."

the big accelerator is many tens of metres in diameter. The round poles of the magnets of the cyclotron (see Fig. 64) are here replaced by a circular-like magnet inside which the particles (protons) being accelerated sweep out trajectories of equal diameter. The trajectories are maintained constant by having the magnetic intensity

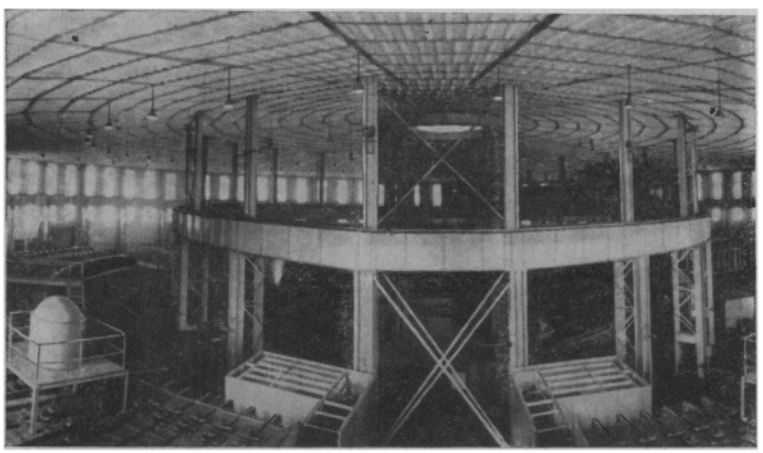


Fig. 65. A general view of an accelerator designed to produce "artificial" cosmic rays in the form of charged particles with an energy reaching 10,000 million electron volts

increase in proportion to the increasing speed of the particles. After a single work cycle has been completed, and a stream of particles of maximum energy smash into a special target, the magnetic field begins to diminish and the machine prepares for the ejection of the next beam of particles.

A large number of investigations have been carried out on the Brookhaven cosmotron, which has been in regular operation since 1953, with beams of protons of 2,200 million electron volts and also with beams of neutrons and charged pi-mesons of slightly less energy. Both neutrons and mesons may be obtained as secondary products from "bom-

bardments" of a target with protons and the ejection of the secondary particles into special channels. This results in neutrons and mesons of very different energies, but the mesons may be "purified" by deflection in a magnetic field to obtain a beam of particles that are hardly distinguishable as to energy (approximately 1,500 million electron volts). In itself, the possibility of obtaining high-energy meson beams of great intensity shows that in a modern cosmotron, processes actually take place that are similar to the formation of secondary cosmic radiation in the earth's atmosphere. The cosmotron can also produce hyperons (in addition to mesons), although in considerably smaller quantities.

ARE COSMIC RAYS A NEW SOURCE OF ENERGY?

Judging from atomic standards, the energy of the individual particles of cosmic radiation is tremendous; however the particles themselves are extremely few in number.

A cosmic ray flux at sea level amounts, on an average, to 1.5 particles per square centimetre per minute (by comparison, the flux of sun light at the earth's surface in clear weather is something like 3×10^{19} photons per square centimetre per minute). It is thus obvious that any attempt to utilize cosmic rays as a natural source of energy is at the outset doomed to failure. Indeed, simple calculations show that if we were able to utilize the entire energy of cosmic rays falling on an area of hundreds of square kilometres we would have an engine capable of developing only about one horsepower.

The rarefied flux of cosmic particles leaves no hope to make effective use of the action of natural cosmic rays on the matter of living and dead nature. Their influence on the life of an organism has not as yet been detected by anyone, and we may rest assured that even the passengers of future interplanetary ships will be out of any grave danger in this respect.

However, quite different is the question of utilizing high-energy charged particles if we have in view artificial methods of obtaining them. Refined and widely used techniques of accelerating particles up to relatively small energies have already resulted in such a new branch of engineering as the production of new chemical elements in the form of artificially radioactive substances, which are in widespread use in biology, medicine, and elsewhere. It may be hoped that the development of a new energy range (thousands of millions of electron volts) will offer new possibilities in this direction.

A "WORLD CYCLOTRON"

Let us now turn to the question of the origin of "real," or primary, cosmic rays. How and where are they born?

At one time this was answered in the following manner. Certain investigators assumed that all or nearly all of the cosmic rays arrive directly from the sun, just as do ordinary rays of light. The verisimilitude of such an assumption is all the more striking since the aurora borealis, for example, is thought at present to be streams of charged particles shooting out of the sun. But in that case the number of cosmic rays registered at a given point on the globe should depend very strongly on the time of day or night and also on the direction of observation. The relatively early observations of cosmic ray intensity had already showed that no direct relationship between them and the sun seemed possible. The most precise experiments showed that within experimental error, involving the influence, for example, of pressure and temperature variations in the atmosphere, the primary radiation remains nearly constant both day and night.

At any rate, it may be stated that if the origin of the bulk of cosmic radiation is in any way related to solar activity, then these particles would have to "wander" about the solar system quite some time in order to lose completely their

initial direction before hitting the earth. Such a chaotic mixture could, it is true, result from the action of a magnetic field, which though it might be very weak would have to extend possibly many millions of kilometres from the sun.

On the other hand, our sun does not differ in many respects from the other stars that make up the gigantic family of our Galaxy, the Milky Way. The absence of any noticeable connection between the primary radiation and the time of day or night does not, it would seem, give any grounds in general to seek its origin in stars. However, the deflecting action of interstellar magnetic fields might make cosmic particles (which had been born in the Galaxy and were now "wandering" about there) absolutely homogeneous both in space and time.

Detailed measurements of cosmic radiation carried out by a large number of workers over a long period of time finally showed that its intensity is not altogether constant, after all: at times it experiences various uneven fluctuations. In certain cases it has been possible to correlate these changes with other phenomena which, it would seem, are of an utterly different character. These phenomena are sun spots, chromosphere eruptions on the sun, magnetic storms (that is, sharp fluctuations of the earth's magnetic field) and, finally, cases of fading in radio communications due to definite perturbations in the ionosphere, which reflects radio signals back to earth. Some investigators tried to explain this relation by the emission of powerful streams of charged particles from sun spots, in which, as was pointed out earlier, there sometimes develop exceedingly strong electromagnetic fields. However, it has not yet been possible to establish any really definite regular relationship in this complex set of phenomena on the earth and on the surface of the sun. Besides, it may be that in this case we are only dealing with a supplementary source of charged particles of relatively low energy, which source has nothing to do directly with the principal flux of cosmic rays in the universe.

Let us try approaching the question from another angle: under what conditions in general can particles arise with such enormous energies as those of cosmic rays?

The first attempt to answer this question was made by Millikan. Having evaluated (from the penetrating power) the energies of those photons which, in his opinion, comprised all primary cosmic rays, Millikan advanced the hypothesis that the origin of cosmic rays is directly connected with the processes of nuclei formation of the most prevalent elements of nature (oxygen, silicon, and others) from their constituents. It turned out later that Millikan was mistaken because his conception both of the nature and the energy of the primary cosmic radiation was erroneous. But it is interesting to note that an analogous concept was fruitful in another important case. Not so long ago, the theorist Bethe, using up-to-date and verified data, showed that the tremendous sources of ordinary solar radiation, which before had been quite unintelligible, might be explained precisely by the formation of complex atomic nuclei from simpler ones; such formation liberates energies that are inaccessible to any chemical reactions.

But the titanic energy of cosmic rays cannot be explained by any known or even possible nuclear transformations. For this reason, some scientists, including Klein and others, surmised the existence of processes in which the entire energy contained in an atomic nucleus is released at once; this results in the total disappearance (annihilation) of such a nucleus, resembling the disappearance of a positron-electron pair accompanied by the emission of a photon. In itself, such a process does not contradict a single one of the fundamental laws of physics, if, of course, we consider that each proton or neutron disappears (as a pair) together with some other particle* and is converted thereby into lighter but very high-speed particles. But the trouble is that even

* Two such particles—the antiproton and the antineutron—were recently obtained artificially by American physicists.

such a tremendous energy, which is thousands and tens of thousands of times greater than that liberated during the annihilation of an electron-positron pair, is still not enough to explain, for example, the energy of a small portion of the cosmic radiation that generates air showers. Following this line of argument, almost fantastic conjectures were put forth concerning the annihilation of whole pieces of matter or even whole worlds.

However, the most successful hypothesis appeared when physicists themselves learned, on the one hand, how to obtain high-energy particles using different types of accelerators, and when, on the other hand, they acquired astrophysical data concerning the existence of electric and magnetic fields about stars and in interstellar space.

One such result was an investigation of the magnetic fields of certain stars, which were found to be something in the nature of gigantic revolving magnets; the magnetic field of such a star varies in the course of several days not only in magnitude but also in direction. This fact was invoked by the Soviet physicist Y. Terletsky and other workers who made the assumption that many stars had such electromagnetic fields and produced calculations that showed the possibility of the acceleration of protons and heavier nuclei up to the relatively high energies that are characteristic of at least the "rank-and-file" particles of cosmic rays.

It was also found that interstellar space as well might serve, in certain conditions, as a titanic cyclotron continuously "fabricating" cosmic rays by accelerating atomic nuclei. Extremely sensitive optical studies showed that matter is always found even in what would seem to be absolutely empty interstellar space, although the average density is vanishingly small, less than one atom per ten cubic centimetres. Besides, there also exist enormous accumulations of interstellar matter (something like "clouds") in which the density of the matter is many times greater. A study of the spectral composition of light that is absorbed in such

"clouds" has shown that to a great extent they consist of ionized atoms, such as hydrogen nuclei, or protons. In its motion, the charged matter comprising part of an individual "cloud" creates electric currents covering vast expanses of space. Calculations carried out by the astrophysicist Alfvén have shown that such currents are capable of producing peculiar magnetic waves.

Utilizing Alfvén's results and data obtained during recent years concerning the prevalence and type of motion of clouds of interstellar matter, another theoretician, Fermi, built and published in 1949 a very curious hypothesis. The chief idea behind Fermi's argument is this. When charged particles of any kind enter the above-mentioned clouds, they are not only deflected by magnetic waves, but can also obtain therefrom a definite energy. The theory indicates that successive collisions of a particle with different clouds should on the whole lead to a gradual accumulation by it of energy, which in certain cases can reach unthinkable values. However, in order to substantiate his hypothesis, Fermi is forced to assume the existence of some source of protons of energy sufficiently great to begin the above-described process of acceleration, despite energy losses by ionization of interstellar matter. For the heavy nuclei, this initial supply of energy proves to be much greater than that for protons.

The problem of the primordial accumulation of energy that was at first one of the principal difficulties in the Fermi hypothesis, was analysed in detail by Terletsky in his work of 1951. Here Terletsky succeeded in finding a better solution to the whole problem by assuming that the initial stage of acceleration of the charged particles takes place near stars, and the succeeding stage in interstellar space. However, the dearth of astrophysical data makes it impossible to construct and verify such theories of the origin of cosmic rays.

Fundamentally new possibilities of solving this involved problem have appeared recently in connection with progress

in a new branch of science, radio astronomy. The employment of very precise and highly sensitive radio receiving apparatus of the radar type has made it possible to establish the existence of a relatively strong radio radiation from the depths of the Galaxy and to detect even individual "centres" of such radiation. There are grounds for believing that a considerable portion of the radio radiation of the Galaxy is caused by electrons of energy of the order of thousands of millions of electron volts which wander about in interstellar magnetic fields together with the protons of cosmic radiation, but, in contrast to the latter, radiate radio waves that are recorded on the earth.

As a thorough analysis of observations conducted by astronomers of past ages has shown, local sources of radio radiation coincide with so-called "supernovae" that exploded long ago. It appears that within our Galaxy, approximately once every 300 years, there appear conspicuously brilliant but short-lived bursts of stars. These dim stars that are hardly visible even in a strong telescope flare up in the course of several days to such an extent that they are visible to the naked eye even during the daytime! Such a rapid (by stellar standards) and tremendous increase in brilliancy is accompanied by an enormous swelling or rather explosion of the whole star, from which there arises a weakly shining nebula that intensively radiates radio-waves.

Calculations carried out by the Soviet investigators V. Ginzburg and I. Shklovsky showed that in the explosion of supernovae a colossal quantity of energy is released, and a considerable portion of this goes to accelerate charged particles. The nature of this acceleration of particles during the explosion of a supernova, apparently resembles the process considered by Fermi with respect to interstellar matter. But here, in contrast to Fermi's hypothesis, we find all the conditions for intense acceleration not only of heavy particles (atomic nuclei) but also of electrons, which move at tremendous speeds in magnetic fields and produce the radio

radiation observed on the earth; therefore, from the intensity of radio radiation it is possible to determine directly also the intensity of the electron flux. These electrons were found to be present in great numbers.

We cannot observe protons (or nuclei in general) in radio radiation because the heavy particles radiate radio waves in magnetic fields just as feebly as do gamma rays in the electric fields of atomic nuclei of matter. However, there are no grounds for thinking that the processes of acceleration do not affect heavy particles; the intensity of these processes proves sufficient to "ensure" all the cosmic radiation* observed on the earth. It is important to note at this point that after the flaring up of supernovae, the intensity of cosmic rays does not necessarily need to increase rapidly and then fall off.

The magnetic fields existing in the interstellar spaces of the Galaxy bend the trajectories of fast particles and do not let them "break loose" from the Galaxy. This is the essential difference between light radiation and cosmic radiation from supernovae. The amount of light is great, but all the photons leave the Galaxy unhindered and create only a brief flash. The number of fast charged particles produced is much less, but nearly all of them wander about inside the Galaxy many millions of years. It is precisely for this reason that the energy contained in cosmic rays may be close to the total energy of stellar light.

Thus, the most natural explanation of the origin of cosmic rays is found in hypotheses connected in one way or another with the concept of acceleration of charged particles in electromagnetic fields which are relatively small in magnitude but tremendous in extent. It is very possible that already during the next decade such theories of a peculiar "universal cyclotron" will finally solve so difficult a problem of modern physics as is the origin of these mysterious messen-

* Electrons are not directly observed on the earth because they dissipate all their energy in radio radiation and other processes.

gers from outer space and their role in the life of the universe with its continuous cycle of different forms of matter eternally in motion. It should be pointed out here that although the energy brought in by cosmic rays falling on the earth is relatively small, the total supply of this energy in all interstellar space may prove to be very great, for example, of the order of the energy of motion of all the stars.

THE PHYSICS OF COSMIC RAYS IN THE LIGHT OF THE MODERN THEORY OF MATTER

The principal questions and problems of cosmic ray physics relate to a study of the constitution of matter, though it would be a mistake to restrict their significance to this branch of science alone. As we have already seen in the section dealing with the origin of cosmic rays, this problem is closely interwoven with questions of the physics of the sun, of stars and interstellar space, and also to some extent with questions concerning the origin and development of celestial bodies. The study of cosmic rays is undoubtedly important to geophysics, for example, in elucidating the problem of the nature of the earth's magnetism and its anomalies and also of the causes of processes that take place in the ionosphere and exert an influence on radio communication. Changes in the isotope composition of the elements of the earth's crust as related to the action of cosmic rays are also of interest in solving geological problems of the distant past of the earth. However, all these questions are of secondary importance when compared to the cardinal problems of the constitution and properties of elementary particles.

In view of the stupendous energies with which the particles of primary cosmic radiation are endowed, they place at the disposal of science a "tool" of truly exceptional strength for penetrating into the heart of matter.

The interaction of cosmic rays with matter not only results in the most profound transformations of atomic nuclei, but also creates (in the process of electron-nuclear shower production) new and hitherto unknown particles—mesons. It was cosmic rays that first made it possible to study mesons directly, in the free state, and not as the nuclear field that binds together the particles of atomic nuclei.

On the other hand, these same mesons (both charged and neutral) provide us both with vivid examples of the existence of matter in a form intermediate between radiation and matter, and with convincing arguments in support of the universal change and interconversion of the elementary particles of matter. Indeed, the mesons that exist in atomic nuclei in a sort of latent state do not in principle differ, as to their role, from the electromagnetic field which binds the atomic nuclei to their surrounding electrons. At the same time, the mesons which are produced in electron-nuclear showers and which later form the penetrating part of cosmic radiation, resemble very much the properties of a stream of nuclear particles of matter, protons and neutrons. They possess, in the same degree, a rest mass and a charge and pass through big thicknesses of matter undergoing even fewer changes than nuclear particles.

And, finally, the incessant transformations of heavy mesons into "ordinary" mesons, of "ordinary" mesons into electrons, and of the latter into photons, and so forth, utterly change the once established and traditional views concerning the immutability of the particles of matter. Whereas the atomism of the recent past rested on the idea of the transformations of matter by mutual rearrangement and combinations of the same nuclear particles, present-day physics explains even the very existence of stable atomic nuclei through the continuous emission and absorption of mesons connected with a constant change in the state of the fundamental nuclear particles, protons and neutrons.

If to this we add the incessant processes of the mutual transformations of light particles of matter (electrons, positrons) and particles of radiation (photons) that take place in cosmic rays, it will then be clear that the new facts about particles of matter are gradually raising atomism to a higher level. At this level, atomism begins to erase the fundamental dividing line between radiation and matter and carries with it the concept of a universal interaction, change, and transformation of all particles of matter.

Г. ЖДАНОВ

ЛУЧИ ИЗ МИРОВЫХ ГЛУБИН

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